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STRUCTURES OF THE WISCONSIN AND TRI-STATE LEAD AND ZINC DEPOSITS.[1]

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THE structural features of the lead and zinc districts of the Mississippi Valley have been studied for nearly a hundred years, as aids to exploration and in relation to the origin of the ores, and apparently the last word has not yet been said. A review of the structural hypotheses which have been formulated brings out clearly the fact that they have been greatly influenced by ideas about the origin of the ore, and in turn have been used as a basis for hypotheses of ore genesis. From the great complex of observational data different investigators have selected different elements for emphasis, and then have used the perspective thus built up as evidence for some favored idea of ore genesis. In some cases the investigator has had such a strong predisposition toward one or another hypothesis of origin of the ore that he has obviously been influenced in the selection of his supporting structural facts from the many available. It will appear, I think, from the following review, based on long familiarity with these districts, that structural generalizations furnish as yet a very insecure basis for any conclusion about the source of the ore. This discussion is confined to structural considerations, and no attempt is made to cover all phases of the problem of ore genesis.

[1] Read before the Joint Session of the Society of Economic Geologists and the Geological Society of America, Tulsa Meeting, Dec. 29, 1931.

The structures and the ideas about them are so numerous and have been studied by so many people, both for scientific and exploring purposes, through so many years, that it would be quite out of the question to attempt a thoroughly exhaustive review within the limits of this paper. Moreover, there are so many repetitions and minor variations of the same points of view that their mere listing would make tiresome reading. To make my point it will suffice to review only the principal ideas which have been put forward during the past thirty years by men whose long familiarity with the fields, or high standing in similar fields of investigation, entitles their views to consideration. It will also serve our purposes to confine our attention to the Wisconsin and Tri-state fields.

Wisconsin-Illinois Field.—All observers of ore-bearing fissures in the lead and zinc district of Wisconsin and Illinois agree that the vertical fissures have predominantly an east-west strike, that this set is crossed by a north-south set, less numerous, that there are many quartering fissures which locally become the dominant ones. Cox's [2] summary of the strike of 1,342 crevices, as shown on the U. S. Geological Survey map, expresses the situation quantitatively and shows many important fissures in all the 10-degree segments of the compass. There are also inclined joints or pitches that have equally various directions.

Since the time of Chamberlin all observers have called attention to the rough parallelism in strike between the dominant east-west system and the axes of the oil rock basins, and to the existence of another set approximately at right angles. On the assumption that oil rock basins represent folding by north-south pressures, several investigators have referred the east-west and north-south joints to the same pressures. Chamberlin,[3] Cox, and Spurr [4] have also referred the inclined joints to these pressures, regarding them as the result of deflection of forces along beds.

[2] Cox, G. H.: "Lead and Zinc Deposits of Northwestern Illinois." Illinois Geol. Survey, Bull. 21, 1914.

[3] Chamberlin, T. C.: "The Ore Deposits of Southwestern Wisconsin." Geology of Wisconsin, vol. 4, pp. 365–571, 1882.

[4] Spurr, J. E.: "Upper Mississippi Lead and Zinc Ores." Eng. & Min. Jour.-Press, vol. 117, pp. 246–250, 287–292, 1924.

On the other hand, Bain,[5] Grant,[6] and Davis[7] regard the oil rock basins in part as folds resulting from north-south pressures and in part as basins of original deposition which have slumped during consolidation, thereby producing both inclined and vertical joints.

The idea that the jointing is related to the oil rock basins has obviously influenced all these descriptions of the joint systems, leading to emphasis on the sets that are parallel and normal to these basins, and referring to the others as quartering or minor, even though Bain and Cox recognize in certain parts of the district a wide variation in the relations of the joints to the longer axes of the oil rock basins.

None of the detailed mapping by any of the investigators above named has disclosed any important faults.

Although Spurr[8] has not studied the district in any detail, he has recently read another pattern into the situation. He chooses as the salient feature the general trend of the principal ore-bearing belts, namely, north-south and northeast-southwest, and then selects for emphasis the fissures crossing these trends at right angles, like "a stack of poker chips," and a subordinate set more or less parallel to the trend of the ore zones. Instead of regarding the joints as caused by the same stresses that produced the oil rock basins, whether compression or slump of original basins of deposition, he relates them to subterranean intrusions (of which there is no local evidence) of about the same trend as the ore zones. Intrusion was supposed to have been followed by subsidence and contraction, producing two sets of fissures, one parallel and one at right angles to the trend of the subterranean intrusion, and both are assumed, though direct observation is lacking, to extend to the unseen intrusive below.

[5] Bain, H. F.: "Zinc and Lead Deposits of the Upper Mississippi Valley." U. S. Geol. Survey, Bull. 294, 1906.

[6] Grant, U. S.: "Report on the Lead and Zinc Deposits of Wisconsin." Wis. Geol. & Nat. Hist. Survey, Bull. 14, 1906. With atlas.

[7] Davis, R. E.: "The Genetic Relation of the Lead and Zinc Ores to the Oil-rock in Southwestern Wisconsin." Thesis, Univ. of Wis., 1906. Unpublished.

[8] Spurr, J. E.: *Op. cit.*

Emmons'[9] approach to the problem is even more general, merely calling attention to the fact that the district lies along a northwest projection of the LaSalle anticline, and that still farther northwest in Minnesota there are faults which "at least . . . show that faulting is not unknown in the upper Mississippi Valley near the mineralized zones." He concludes that "the major zone of deformation of the Mississippi Valley may be regarded as a foothill system of faults and folds that are related to the late Paleozoic deformation which produced the Ouchita, Arbuckle, Wichita and Appalachian systems." He makes no attempt to relate the detail of the folds, joints, and faults of the ore zone to the major deformation. As a matter of fact, no major faults have been observed, and the district shows no trace of the LaSalle anticlinal structure. The minor folds have east-west axes. The general dip is at a low angle to the southwest, corresponding to the position of the district on the southwest limb of the southerly pitching Paleozoic anticline of southern Wisconsin, the axis of which does not correspond either in position or direction with the LaSalle anticline.

Still another concept has been emphasized by the Geological Department of the University of Wisconsin and by the Geological Survey of Wisconsin, as a result of field studies in southern Wisconsin, namely, that not only such local features as the oil rock basins may be explained largely by original deposition and slump, but that a very large part of the joints and minor folds in the Paleozoic rocks are to be attributed to slump during consolidation on the irregular basements formed in successive erosion periods; also that weathering emphasizes and causes much of the shallow jointing which can be seen at the surface. This view minimizes the emphasis on any pattern, allows for a wide range of strike and dip, and particularly allows for discontinuity, both vertical and horizontal, which is one of the characteristic features of the jointing as a whole.

Relations of Structure to Ore Genesis.—We may now consider

[9] Emmons, W. H.: "The Origin of the Deposits of Sulphide Ores of the Mississippi Valley." Econ. Geol., vol. 24, pp. 221–271, 1929.

how these highly varied structural concepts have affected conclusions as to the origin of the ores.

Without exception, the investigators who have had opportunity to make long-continued detailed studies have agreed that the ores are the result of some combination of original deposition in the containing sediments, with later concentration by lateral, upward, and downward moving solutions, but all limited below by the impervious oil rock basins. The absence of observed faults or fissures known to extend to great depth has been an important consideration in reaching this conclusion. Also all of this group have noted the geographic and stratigraphic relations of the ore to the oil rock basins, and have naturally given principal attention to the joints in the vicinity of these basins. Because of this, it is easy to account for a certain over-emphasis on the kinds of joint patterns that might be explained by some combination of lateral compression and slump, which is supposed to be the cause of the basins, and to minimize the many additional fissures without symmetrical relations to such basins.

Spurr, on the other hand, with a strong predisposition toward hot solutions from igneous sources below as a source of the ores, and without detailed knowledge of the district, naturally sought for evidence of deep fissuring and faulting, and failing in this by direct observation, he assumed their presence on the basis of the relations of the fissures to general ore trends, which in turn were assumed to be controlled by igneous disturbance from below. He therefore emphasized only such fissures as have symmetrical relations to these general ore trends. A glance at the Geological Survey map showing the trends of all the fissures, and comparison with generalizations of other observers, are enough to show the extent to which subjective consideration has been read into the structural complex, because the variations from the assumed pattern are so numerous and widespread.

Emmons, also with a predisposition to an igneous source from below, merely assumed that the location of the district along the trend of the LaSalle anticline, as well as the existence of faulting to the northwest in Minnesota, is enough to create a presumption

that this district has suffered an orogenic disturbance, and therefore deep faulting, at the general time of the Appalachian revolution, which time elsewhere was marked by local igneous intrusions.

It may be noted that even if deep faults and fissures were to be proved by direct observation to extend to intrusive igneous rocks below, the burden of proof would still be on the assumption that the ore-depositing solutions came from igneous sources below, in view of the occurrence of the ore above impervious oil rock basins, to say nothing of the nature and paragenesis of the ore minerals, and the lack of any evidence whatever of igneous intrusions or of distinctive hot water minerals or of thermal metamorphism in the ore district itself.

Tri-state Field.—In the Tri-state field it is not surprising that the complex of joints, faults, folds and breccia zones of various ages has thus far restricted attempts to reduce it to a single comprehensive pattern. Explorers, miners, and investigators of the origin of the ore have made many attempts to do so. They could hardly avoid it. Many local lineaments of structure have proved empirically useful in exploration, but the extrapolation of such elements over the district as a whole has not thus far been successfully accomplished.

Buckley and Buehler,[10] in their report on the Granby area and in other general papers on the district, were content merely with listing the principal directions of jointing, which they give as: N. 30° E., N. 45 to 50° W., N. 60 to 70° W., N. and S., N. 40 to 50° E., and N. 65 to 70° E. They regarded the joints as principally due to differential settling of the beds caused by solution of the limestone. The possibility of extensive faulting connected with the ore bodies is minimized, and as a corollary it is concluded that there are no fault breccias in this district, the so-called brec-

[10] Buckley, E. R., and Buehler, H. A.: "The Geology of the Granby Area." Mo. Bur. of Geol. & Mines, vol. 4, 2d ser., 1906.

Buckley, E. R.: "Lead and Zinc Resources of Missouri." Am. Min. Cong., Rept. of Proc., 10th Ann. Sess., 1908, pp. 282–297.

Buckley, E. R.: "Geology of the Disseminated Lead Deposits of St. Francois and Washington Counties." Mo. Bur. of Geol. & Mines, vol. 9, 2d ser., 1909.

cias being regarded in part as basal conglomerates and in part as a result of solution.

Buehler's later observations in Missouri indicate that the major fractures of Missouri have a northwest-southeast direction, with a minor set at approximately right angles. This varies, however, with individual camps. The original fracturing in the Boone formation, in which the ores are principally located, is regarded as the result of slump about ridges or knobs in the pre-Cambrian basement rocks. A recent survey of the district with magnetometer, under the direction of Mr. Buehler, shows that the ores are not located along magnetic highs, which are regarded as reflections of the pre-Cambrian relief.

Bain and Adams [11] reported the presence of deep fractures and faults of 100 to 150 feet displacement, which were attributed to compressive stresses, followed by vertical oscillations and warpings. The period was assumed to be that of the Ouchita mountain orogeny. Breccias were described as occurring along the same zones as a result of the same forces. Bain regarded the ore runs as closely associated with the faulting, and used them as evidence of faulting. The ore was supposed to have been concentrated by artesian circulation moving upward through deep fissures and breccia zones. Many details were given of the distribution of faults, joints, and fissures, but no attempt made to generalize a pattern for the region. Much of the evidence cited for deep faulting has subsequently been interpreted by Siebenthal and others as the result of solution and slump, often following the steep walls of the pockets and patches of Pennsylvanian shale, which unconformably overlie the ore-bearing Boone formation.

In the early part of Siebenthal's [12] long-continued work in the

[11] Bain, H. F.: Preliminary Report on the Lead and Zinc Deposits of the Ozark Region. With chapters on the physiography and geology, by George I. Adams. U. S. Geol. Survey, 22nd Ann. Rept., pt. 2, pp. 23–228, 1901.

[12] Siebenthal, C. E.: "Structural Features of the Joplin District. ECON. GEOL., vol. 1, pp. 119–128, 1906.

Siebenthal, C. E., and Smith, W. S. Tangier: "Description of the Joplin District." U. S. Geol. Survey Atlas, Joplin district folio (No. 148), 1907.

Siebenthal, C. E.: "Origin of the Zinc and Lead Deposits of the Joplin Region, Missouri, Kansas, and Oklahoma." U. S. Geol. Survey, Bull. 606, 1915.

Joplin district, he also put the emphasis on the relation of the ores to underground drainage channels, following fissures and breccia zones, which strike principally N. 25° W. and N. 50° E. These he attributed to torsional stress at the close of the Boone limestone deposition (pre-Pennsylvanian), and independent of the Appalachian revolution following the Pennsylvanian. The joint system resulting from torsion was assumed to have predetermined the directions of the ore-bearing breccias, which were formed at a later period. Even the brecciation of the interbedded Grand Falls chert was ascribed to horizontal shear developed by the torsional stresses. He doubted the existence of deep general faulting, but recognized minor faulting, mainly resulting from solution and slump. "The slickensided limestone walls, the broken character of the shale at the steeper peripheral contacts of the shale patches, and the local zones of brecciation, which have led to the ascription of deep faulting to the Joplin district, and have introduced such confusion into its structural geology, are no doubt due to such readjustments."

In later work in the Miami district, Siebenthal [13] maps and describes the linear Commerce run of ore, trending north-northeast, following the trough-shaped bottom of the Cherokee shale. He considers the trough not due to faulting but to underground solution, directed and controlled by a special system of fracturing, without evidence of dislocation. Other runs are noted in a north-northwest direction, with the same explanation.

So much of the ore of the Tri-state field occurs along the steep flanks of Pennsylvanian troughs or deeps that the mapping of these troughs has proceeded steadily by local geologists and engineers and by the U. S. Geological Survey. Three sub-shale maps of

[13] Siebenthal, C. E.: Contour map of the surface of the beds underlying the Cherokee shale in a portion of the Picher district, Oklahoma, showing relations of ore bodies to the surface contoured. U. S. Geol. Survey, 1925. With explanatory text.

Contour map of the surface of the beds underlying the Cherokee shale in the area between Cardin and Commerce, in the Picher district, Oklahoma, showing geographic relations of ore bodies as worked to the surface contoured and to the Commerce deep shale trough, together with a tranverse cross section of the trough. U. S. Geol. Survey, 1927. With explanatory text.

parts of the Tri-state field have now been issued by the U. S. Geological Survey. Ageton,[14] the author of the last of these maps, concludes that "the relationships between the strike of the ore-bearing fissures and the strike of the shale troughs has never been fully determined, but both seem to follow the same general trend." The ore-bearing fissures do not penetrate the limestone bars that separate the troughs. He offers no opinion as to faulting or deep fissures.

Spurr [15] emphasizes the tendency of the ores for the entire field to follow east-northeast and north-northwest runs. He publishes a generalized sketch indicating his emphasis on these directional elements, and concludes that the ore solutions gained access to the rocks through a definite system of deep fractures in the same directions. The breccias are regarded as largely the result of the same movements. The cause of the movements, as in the Wisconsin district, is attributed to hypothetical subterranean intrusion parallel to the principal east-northeast trend, followed by subsidence which developed fissures and breccias parallel and normal to the trend of the intrusion.

Emmons [16] concludes that "the region is in the strike of the Seneca fault zone which contains faults with vertical displacements of several hundred feet. These faults are not followed into the main ore-bearing district although faults with small throw, some of them parallel to the faults of the Seneca group, are recognized at several places." He also indicates on a map what he regards as a major zone of deformation extending from the fluorspar district of Kentucky westward through Missouri and then southwestward into Oklahoma, and implies both by the map and by his description that the structure of the Tri-state field is related to this major zone. He indicates the existence of north-

[14] Ageton, Richard V.: Contour map of subshale surface of lead and zinc mining district of northwestern part of Quapaw Reservation, northeastern Oklahoma, showing the relation of the mined ore bodies to the sub-shale topography. With explanatory text. U. S. Geol. Survey, 1931.

[15] Spurr, J. E.: "Ores of the Joplin Region (Picher District)." Eng. & Min. Jour., vol. 123, pp. 199–209, 1927.

[16] Emmons, W. H.: "The Origin of the Deposits of Sulphide Ores of the Mississippi Valley." ECON. GEOL., vol. 24, pp. 221–271, 1929.

east and southwest runs parallel to the Seneca faulting in the Miami district, particularly the Commerce fault, which he regards as a great zone of deformation. Other ore runs trend northwest. "There is thus a rude conjugation of runs or belts of deformation, which suggests compressive stresses. There are faults of the Seneca group that have throws of several hundred feet and one has a throw of 700 feet. It appears probable that there are faults in the Joplin district of sufficient magnitude to displace any shales that lie below the ore bodies sufficiently to allow metallizing solutions to rise to the region of the brecciated Boone formation." Breccias are related to faulting, differential movement along beds, and slump caused by solution. The deformation is generally related to the Appalachian revolution and to igneous intrusions of that time.

It will be noted that Siebenthal stressed the fact that the fissures controlling the distribution of the ore bodies were formed at the close of the Boone formation and were entirely independent of the deformation which occurred in the later Appalachian revolution.

Some of the most recent and exhaustive studies of structure have been made by Fowler and Lyden,[17] in the western part of the Tri-state field. Their work has not been extended in the same detail to other parts of the district. They see, in the Commerce run, evidence of a shear zone striking northeasterly and made up of many parallel fissures and accompanied by much brecciation. Northwesterly runs in the same region are regarded as complementary shear zones developed at the same time by compressive stresses in a north-south direction. The shear zones are curvilinear. In addition they note north-south fissures which they regard as tensional and caused by the same stresses that produced the northeast and northwest systems. Compression and shortening of the mass are regarded as generally north-south, and consequently tension and elongation of the mass would be at right angles thereto. The entire system is thought to have some simi-

[17] Fowler, George M., and Lyden, Joseph P.: "The Ore Deposits of the Tri-state District (Missouri-Kansas-Oklahoma)." A. I. M. M. E. Tech. Pub. 446, 1932.

larity with the system of fractures at Butte, with which both men have long been familiar, and is ascribed to much the same kind of horizontal distortion of the district as had been suggested for the Butte district by Leith and Mead in the course of apex litigation in that camp. Indeed, it is a clear case of extrapolation of a mechanical concept of Butte structure to a far distant and in many respects dissimilar field. Convinced of the correctness of their structural pattern and its origin, Fowler and Lyden assume that the fissures are deep-seated, and they favor the hypothesis of rising hot solutions from below, as in the case of Butte.

What these men describe as shear zones have been mapped by Siebenthal and Ageton as solution channels in which the Cherokee shales have been deposited, without positive evidence of faulting. The classification of fissures as shearing and tensional by Fowler and Lyden is clearly influenced by the requirements of the mechanical hypothesis which they have adopted. Others have not been able to make such a classification on the basis of observation of the fissures themselves.

Weidman,[18] in his forthcoming report on the Picher district (Oklahoma Geological Survey), recognizes much the same pattern as that presented by Spurr and Fowler. However, he regards the Miami syncline as a major structural feature of the Picher district, and relates the structural pattern to this feature. The breccias are attributed to deformation and not to weathering. He also recognizes a fracture system older than the folding and brecciation. He favors the hydrothermal theory of the origin of the ore.

Finally, as in the Wisconsin district, evidence is rapidly accumulating that although part of the deformation of this general region has been caused by regional stresses of an orogenic nature at different periods, much of it is to be attributed to deposition on an irregular pre-Cambrian basement and on irregular erosion surfaces formed later, followed in each case by shrinkage and slump as the beds consolidated. Since the early work of Buckley and Buehler on the Granby area there has been increasing recog-

[18] Weidman, Samuel, personal communication.

nition of this kind of deformation, and it is now given a very prominent place by the Missouri Geological Survey, oil geologists,[19] and others.

Of especial interest is the varying interpretation of breccias in their bearing on ideas of ore genesis. These are widespread in the Tri-state field, and they constitute the host for much the greater part of the ore. In earlier interpretations these were regarded as mainly friction breccias, no matter what the form of their occurrence, and this idea is carried through to the present by advocates of rising hot solutions. From the start, minor parts of the brecciation were recognized by nearly all observers as resulting from solution and slump of limestone near weathered surfaces. An important shift of emphasis came with the work of Buckley and Buehler on the Granby area (see p. 410), when they classified the breccias as the result of solution and slump or as conglomerates. When, later, the Grand Falls chert breccia was found to extend in a great sheet down the dip into the Miami end of the field in a continuous layer 15 to 40 feet thick, roughly parallel to the bedding of the overlying and underlying sediments, it became difficult to account for it as a friction breccia, although this idea still persists among those who are trying to prove extensive faulting. Ulrich,[20] in his stratigraphic studies of this general region twenty years ago, identified the Grand Falls chert as an old erosion surface, but this interpretation more or less escaped notice among the structural geologists working in the ore bodies until recent years. I had occasion to call attention to it in connection with my study in 1925[21] of the silicification of old erosion surfaces. Since that time Buehler, Dake and others, of the Missouri Bureau of Geology and Mines and the Missouri School of Mines, have been able to identify the Grand Falls chert

[19] Blackwelder, Eliot: "The Origin of the Central Kansas Oil Domes." Bull. Amer. Assoc. Petrol. Geol., vol. 4, pp. 89–94, 1920.

Powers, Sidney: "Reflected Buried Hills and Their Importance in Petroleum Geology." ECON. GEOL., vol. 17, pp. 233–259, 1922.

[20] Ulrich, E. O.: "Revision of the Paleozoic Systems." Bull. Geol. Soc. Amer., vol. 22, pp. 281–680, 1911.

[21] Leith, C. K.: "Silicification of Erosion Surfaces." ECON. GEOL., vol. 20, pp. 513–523, 1925.

and other breccia beds as old erosion surfaces, and in fact, by the microscopic study of residuals from the leaching of the cherts, have been able to identify particular horizons in many parts of Missouri. The evidence of the surficial origin of the greater part of the chert breccias now seems to me conclusive. Also I am entirely unable to conceive of structural deformation parallel to the bedding which could produce such results as the Grand Falls chert beds, even if the district had undergone far more deformation than is now apparent.

Relations of Structure to Ore Genesis.—Comparing these various views, it is apparent that advocates of deposition of the ore by rising waters, whether hot or cold, have desired to see evidence of deep fissures and faults controlling the runs of ore, and have not hesitated to assert definitely that such fractures exist, even though their observational evidence was of a highly circumstantial variety. Although other than structural evidence has been cited by advocates of hot rising solutions, such as assumed zonal arrangement of ores and the existence of scattered dikes in the same formations in distant areas, nevertheless the existence of deep faulting and fissuring has bulked large in their argument,—so much so that the impression has been created, particularly by Spurr, Emmons, and Fowler, that the acceptance of deep faulting carries with it a strong presumption in favor of rising hot solutions. To others there is an obvious *non-sequitur* in this argument.

On the other hand, advocates of deposition of the ores by descending solutions have been somewhat indifferent to the possibilities of deep fracture, and have been inclined to emphasize the absence of positive evidence for such deep fractures. This group regards the fissures, minor faults, ore-bearing breccias, and ore trends, not as evidence of deep fracture, but in the main as the result of solution and slump at or near the erosion surfaces, present or past.

The advocates of the hypothesis that the ores result from rising hot solutions date these solutions with the igneous intrusions which accompanied and followed the Appalachian revolution.

They have been led to do this because the rare dikes which have been found in various parts of the Mississippi valley away from the lead and zinc districts are so dated, and if it could be established that this was also the time of the fracture system into which the ores were introduced, a certain plausibility is added to their hypothesis. Spurr goes even further and sees in the pattern of fractures evidence of an immediately underlying intrusion.

On the other hand, the group which has regarded the ores as deposited by meteoric solutions, either ascending or descending, or both, has in the main dated the ore-bearing fissures as pre-Carboniferous and not that of the main Appalachian-Ouchita orogeny which affected the Carboniferous as well.

Conclusion.—The Mississippi valley lead and zinc districts have repeatedly suffered slight disturbance by regional stresses, and in addition to the structures so produced many joints, faults, and breccias have resulted from slump during the consolidation of the strata on an uneven basement and the effects of solution and weathering on erosion surfaces, both past and present. The disentanglement and classification of the structures produced by these different forces and at different times have not yet been successfully accomplished. In almost every case attempts to do so have resulted in over-simplification and distortion of the perspective afforded by purely inductive study. The desire to find confirmatory evidence of some hypothesis of ore genesis has clearly influenced the structural interpretations. Much of the structural evidence is therefore discredited as a sound basis for interpreting the origin of the ore. Other evidences of ore genesis are not here considered.

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THE COMPOSITION OF VEIN SOLUTIONS AS SHOWN BY LIQUID INCLUSIONS IN MINERALS.

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SOME recent work by Buerger[1] called attention to the presence of liquid inclusions of considerable size and quantity in galena from Joplin, Missouri. This discovery lends new interest to a subject which a few decades ago received considerable attention. Information on liquid inclusions obtained by the early investigators seems to have been largely neglected or forgotten in the discussions of vein solutions that have been published in the literature during the last few years.

The present writer has examined galena and other ore minerals from a number of localities for liquid inclusions, particularly with respect to their composition. Results were obtained that, although only preliminary in nature, pending complete quantitative analyses, seem of some interest. It is the purpose of this paper to review the literature which has a bearing on the subject in order to furnish a background for further work, and to give the preliminary results obtained in the study of the liquid inclusions in galena and sphalerite. Principal interest is attached to the fact that certain types of liquid inclusions undoubtedly represent samples of the solution that deposited the minerals.

INCLUSIONS.

The inclusions in minerals which have been described are of liquid, gas, crystals, or glass, or some combination of these. The crystals or minerals that occur alone in solid form as inclusions, such as rutile in quartz, are outside of the present discussion.

Inclusions of glass are principally found in the phenocrysts of

[1] Buerger, M. J.: The Negative Crystal Cavities of Certain Galena and their Brine Content. Amer. Min., vol. 17, June, 1932.

lavas. Liquid inclusions have been found in a large variety of rocks and minerals. They commonly consist of a liquid (solution or carbon dioxide or both) with a bubble, or a solution with a precipitated crystal, crystals or irregular mass with a bubble.

The extended list of minerals from which inclusions have been described illustrates their diversity. Some minerals containing fluid inclusions are, quartz, feldspar, topaz, ruby, sapphire, beryl, aquamarine, fluorite, calcite, sodalite, nephelite, danburite, spinel, gypsum, halite, cassiterite, sphalerite, galena, and native sulphur.

Size of Cavities containing Liquid Inclusions.—The size of the cavities and their number vary greatly. Some described by Hidden [2] in quartz from North Carolina, contained cavities filled with liquid which were two and one-half inches long and one-quarter inch wide. He also mentions inclusions in quartz from Herkimer County, New York, 10 mm. in their longest diameter. Galena and sphalerite from the Tri-State district contain some cavities with solution, up to a centimeter and more in length.

More commonly the inclusions in quartz from veins and igneous rocks are measured in hundredths to thousandths of a millimeter. They may be present in great numbers; Sorby [3] estimated that commonly in vein quartz there are upwards of a thousand millions to the cubic inch and states they are the chief cause of the whiteness of that mineral. Vogelsang [4] estimates the inclusions in quartz from the granite of Johann-Georgenstadt, Saxony, to number more than a hundred thousand to the cubic millimeter. This abundance is commonplace to microscopic workers.

Form of Liquid Inclusions.—The cavities are mainly irregular in outline, with rounded curved outlines or irregularly angular. A prominent variety of this is extension along a plane, giving an irregular lens-like form, or along a line, giving an irregular tubular form. Negative crystal cavities are comparatively rare, but quartz containing cavities showing the prism and two rhombo-

[2] Hidden, W. E.: A Phenomenal Find of Fluid-bearing Quartz Crystals. Trans. N. Y. Acad. Sci. 1: 132–133, 1881–82.

[3] Sorby, H. C.: On the Microscopical Structure of Crystals. Quart. Jour. Geol. Soc. 14: 474, 1858.

[4] Vogelsang, H.: Pogg. Annals, Ser. V: 17: 263, 1869.

hedral terminations appears to be fairly abundant in some quartz-bearing porphyries,[5] and the cavities in galena[6] may show octahedral and cubic planes.

Arrangement.—Some fluid inclusions are formed at the same time as the enclosing mineral (primary) and others are distinctly later (secondary). Both kinds have been produced experimentally, the primary type by Sorby[7] and secondary examples by Laemmlein.[8] It is, however, not always possible to distinguish between them. Sorby has shown by artificially crystallizing a number of compounds that crystals which form in free space contain the inclusions, developed in growth zones of the crystals, i.e. parallel to certain or all of the crystal faces, or wholly irregularly disposed throughout the crystal. These same features have been observed in minerals that crystallized in open veins or cavities. It is obvious that liquid inclusions which are in a crystal that formed and has remained since in open space will be only of the primary type. An arrangement along the boundary between two lineages[9] is common in galena crystals that have developed in free space, also this is the common arrangement in the sphalerite which the writer has examined.

Work done since Sorby's time has proved that secondary inclusions are more prevalent than the early workers realized. Some of the mistakes made by Sorby on interpretation of these features in rocks and some of the criticisms of his conclusions are without doubt based on a lack of knowledge that both types may be present in the same minerals when in rocks or solid masses that may be sheared or fractured. Clearest evidence for secondary origin is where lines or planes containing the cavities pass straight and uninterruptedly across several crystals. These have proved to be resealed fractures in numerous descriptions,

[5] Bosscha, J.: Ueber gewisse Einschlüsse im Quarz. Z. Krist. 13: 55–56, 1888.

[6] Buerger, M. J.: *Op. cit.*

[7] *Op. cit.*, pp. 453–500.

[8] Laemmlein, G.: Sekundäre Flussigkeitseinschlüsse in Mineralien. Z. Krist. 71: 237–256, 1929.

[9] Buerger, M. J.: The Significance of "Block Structure" in Crystals. Amer. Min. 17, pages 177–191, 1932.

where they have been described in quartzite, gneiss, granite, peridotite, and other rocks.[10]

The rift and grain in granite, which are planes of easy fracturing utilized in quarrying the rock, have been shown by Dale [11] to be due largely to closely spaced parallel sheets of fluid inclusions in the quartz crystals of the granite. His descriptions indicate that they are a widespread and common phenomenon. They are regarded by him as having been formed during the final stage of crystallization of the granite and as due to "crystal strains." It might be considered that the crystals of galena and sphalerite, to be described later, contain secondary rather than primary inclusions, but this is an impossibility, since the crystals have obviously grown in open cavities and bear no sign of deformation of any kind.

Composition.—Considering only the primary fluid inclusions. it would seem necessary to assume that they represent small portions or samples of the solutions that deposited the minerals in which they are inclosed. Certain features indicate that they also may contain other substances than those essential to transport the mineral in which they are found. Frequency of correlation between constituents in the fluid inclusions and the enclosing mineral should have significance. This reasoning has been anticipated, by Sorby [12] experimentally. Most of the chemical analyses of fluid inclusions are old and usually it is impossible to state whether they include primary inclusions or secondary or both types. It appears obvious that the secondary inclusions in a mineral are capable of transporting enough mineral substance to seal themselves in the fracture along which they are found. The composition of inclusions has often been studied by spectro-

[10] Cross, C. W.: Studien über Bretonische Gestein. Miner. u. Petrogr. Mitt. N. F. 3: 373–376, 1881; Hicks, H.: On the Cambrian Conglomerates. . . in Anglesey and Carnarvonshire. Quar. Jour. Geol. Soc. 40: 194–195, 1884; Judd, J. W.: On the Tertiary and Older Peridotites of Scotland. *Idem* 41: 375–376, 1885; Judd, J. W.: On the Relations between the Solution Planes of Crystals and those of Secondary Twinning. Miner. Mag. 7: 82–83, 1886.

[11] Dale, T. Nelson. The Commercial Granites of New England. U. S. Geol. Survey, Bull 738: 17–26, 1923.

[12] *Op. cit.*, pp. 457–460.

scopic means and the microscope has given much additional information. Sorby [13] states that the inclusions in the quartz of the rocks at Cornwall, England, contain water, with chlorides of potassium and sodium, and sulphates of potash, soda, and lime in solution, and the solution often gives a decided acid reaction.

Pfaff [14] concluded that the mechanically enclosed fluid in feldspar and quartz from granites was water with sodium chloride in solution.

Vogelsang and Geissler [15] found carbon dioxide and water in quartz from Saxony granite.

Travers' [16] results obtained from a granite from Peterhead indicate carbon dioxide and also carbon monoxide as present in the quartz.

Quartz from the Providence Mine, Nevada City, California, which contained abundant fluid inclusions, was examined by Lindgren and Steiger [17] who dissolved the powdered quartz in water, filtered it, and analyzed the residue (A) and filtrate (B).

	A	*B*
SiO_2	3	28
$Al_2O_3Fe_2O_3$	2	2
CaO	13	44
MgO		1
$(KNa)_2O$		29
So_3		78
Cl		5
	18	187

They state: "The result shows the presence of sulphates of calcium and alkaline sulphates together with very little chloride."

Quartz crystals [18] from Dauphine were found to contain in

[13] *Op. cit.*, p. 487.

[14] Pfaff, Fr.: Pogg. Annals, 143: 610–620, 1871–72.

[15] Vogelsang, H., and Geissler, H.: Ueber der Flussigkeitseinschlusse in gewissen Mineralien. Pogg. Annals. Ser., vol. 17: 56–75, 1869.

[16] Travers, M. W.: The Origin of Gases Evolved on Heating Mineral Substances, etc. Proc. Roy. Soc. 64: 135–136, 1898–99.

[17] Lindgren, W.: The Gold Quartz Veins of Nevada City and Grass Valley Districts, California, U. S. Geol. Survey, 17th Ann. Rept. 2: 130, 1895–96.

[18] Furst Zu Salm-Horstmar: Bergkristalle enthalten chlor-metall. N. Jahrb. Miner. Geol. 54: 1853.

the inclusions chiefly potassium chloride with only a trace of sodium chloride; sodium and potassium chloride were both found in quartz crystals from New York and Silesia, and traces of calcium and sulphate were found in the quartz from all three localities.

Quartz from the syenite at Laurvig in southern Norway contains cubes of a salt held in fluid inclusions which Zirkel [19] determined by spectroscopic and chemical means to be sodium chloride. Two analyses of the fluid inclusions in quartz from the Alpine veins are given by Königsberger and Müller,[20] as follows:

(*a*) Quartz from Bachistock		(*b*) Quartz from Aaremassiv	
H_2O	83.4	H_2O	85.
CO_2	9.5	CO_2	5.
Na	2.0	Na	2.5
K	0.7	K, Li	1.5
Li	0.2		
Ca	0.3	Ca	0.3
Cl	1.6	Cl	1.5
So_4	0.5	SO_4	0.7
CO_3	1.8	CO_3	3.5

Spectroscopic checks made for Na, K, Li, and Ca in the first analysis gave strengths of spectral lines in accordance with analytical results. Similarly, a check test, presumably microchemical, with platinum chloride, gave Na: K about 3: 1.

Isotropic cubes which have been precipitated by the solution in cavities have been reported in a number of minerals and in a wide variety of geological relationships.

In view of the results obtained by spectroscopic and chemical means on the saline solution in inclusions, where Na usually predominates over K, it appears likely that the cubes are in most cases sodium chloride rather than potassium chloride. However, since potassium is introduced into vein walls during the process

[19] Zirkel, F.: Mikromineralogische Mittheilungen. N. Jahrb. Miner. 801–806, 1870.

[20] Königsberger, J., and Müller, J. W.: (*a*) Versuche über die Bildung von Quartz und Silikaten. Centr. Miner.: 76, 1906. (*b*) Versuche über die Bildung von Quartz und Silikaten. Centr. Miner. 341, 1906.

of sericitization and sodium is taken away, it might well be that a series of analyses of inclusions in quartz formed very early in the vein sequence would differ in the relative proportions of these two elements from that contained in quartz formed later and during sericitization. Since sericitization of wall rock is a process which probably takes place early in the sequence of mineralization of a vein,[21] most of the quartz may contain solutions which have received additions of considerable sodium from the wall rocks. This question merits future quantitative chemical investigation.

Presence of the cubes indicates that the solution in the cavities had a high concentration of sodium or potassium and chlorine when the cavity was sealed. Falling temperature has lowered the solubility with resulting precipitation of the cubic crystals. Initial high temperature is of course one of the essentials for their formation, and hence they may be expected mainly within or in the close vicinity of igneous rocks. Such is the case, for some are found in granites, diorites, and gneisses, but the most common occurrences are within the late differentiates of granitic rocks, such as porphyries. Since the chlorides appear to be an important part of the metal-carrying solutions, this occurrence in porphyries, as at Clifton-Morenci, Arizona,[22] Bingham Canyon, Utah,[23] Ely, Nevada,[24] and Eureka, Nevada,[25] Cornwall, England,[26] and Cimarroncito District, New Mexico,[27] gives proof of initial high saline content. Evidence unfortunately does not indicate whether the fluid inclusions containing cubic crystals at these places are partly of primary origin. Some of the inclusions and the quartz in which they are found at these places are definitely later than the crystallization of the porphyry. Possibly all the inclusions of such high salt content are slightly later.

21 Lindgren, W.: Mineral Deposits: 614, 1928.
22 Lindgren, W.: U. S. Geol. Surv. Prof. Paper 43: 213–218, 1905.
23 Butler, B. S., et al.: U. S. Geol. Surv. Prof. Paper 111: 358, 1920.
24 Spencer, A. C.: U. S. Geol. Surv. Prof. Paper 96: 100–101, 1917.
25 Iddings, J. P.: U. S. Geol. Surv Mon. 20: 345, 1892.
26 Harker, A.: Petrology for Students: 106. Cambridge Univ. Press, 1923.
27 Lindgren, W., et al.: U. S. Geol. Surv. Prof. Paper 68: 107, 1910.

Of interest in considering the segregation of chlorine in quantity along with certain granitic differentiates is the fact that no occurrence of cubes of NaCl or KCl in fluid inclusions has been found by the writer to be recorded in pegmatites, although numerous references to fluid inclusions in pegmatitic quartz are found in the literature. It would appear from the present data that the differentiation of a granitic rock to pegmatite does not commonly include chlorine in the pegmatite fraction; corroborating evidence is that the apatite connected with pegmatitic dikes which are related to acidic igneous rocks is usually fluor-apatite rather than the chlorine-bearing variety. The lack of substantial amounts of sulphide ore minerals in granitic pegmatites may possibly be correlated with a lack of abundant chlorine-bearing solutions. Very concentrated solutions (a saturated solution of sodium chloride at 20° C. contains 36 gr. of NaCl to 100 cc. of water) of chlorides have been present in the formation of some minerals of high temperature type. Precipitated cubes of what is quite certainly a chloride, probably sodium chloride, have been reported from topaz, spinel, and emerald, and some of these from widely scattered localities. They have also been reported in vein quartz where associated mineralization shows high-temperature affiliations.[28]

Inclusions of liquid carbon dioxide early attracted much attention and it is reported as of widespread occurrence in quartz. It appears alone with a bubble or with water or saline solution, and may be readily recognized by heating the section to about 30° C., which approximates its critical temperature. In addition to this manner of determination, spectroscopic and chemical means

[28] Sorby, H. C.: On the Microscopical Structure of Crystals. Quart. Jour. Geol. Soc. 14: 453–500, 1858; Sorby, H. C., and Butler, B. S.: On the Structure of Rubies, Sapphires, Diamonds, and Some Other Minerals. Proc. Roy. Soc. 17: 292–302, 1868–69; Winchell, A. N.: Notes on Tungsten Minerals from Montana. Econ. Geol. 5: 161, 1910; LaCroix, A.: Mineralogie de La France. 3: 38, 1901–09; Lindgren, W., and Whitehead, W. L.: Deposits of Jamesonite near Zimapan, Mexico. Econ. Geol. 9: 455–457, 1914.

See also previous reference to the "porphyry" or disseminated copper deposits. These deposits usually contain molybdenite as an associated mineral.

have been used in some cases. It is found in quartz from granite, late quartz from pegmatite, and in veins.[29]

Some smoky quartz from Branchville, Connecticut, which contained liquid CO_2 inclusions along with water solutions, was examined by Hawes [30] and analyzed by Wright. The gases alone had the following composition: CO_2, 98.33; N, 1.67; H_2S, SO_2, H_3N, F, and Cl (?), trace; total, 100.00. Bituminous matter was also present in the quartz.

Hydrocarbons or petroleum-like substances have been reported as liquid inclusions in minerals, *e.g.* quartz [31] and fluorite.[32]

Other Substances Found in Fluid Inclusions in Transparent Minerals.—Perhaps the most interesting substances are the small opaque and nearly opaque crystals and rods that may occur in the fluid cavity. Some of these have been regarded as specularite. These small deposits of heavy metal minerals have been observed and reported, chiefly in high-temperature relations. This is probably dependent on the relative solubility of the metals in the solutions at different temperatures although the relative proportions of the chlorides to water also appear to vary with temperature of solution, as is suggested by the preceding discussions. Hence, a concentrated chloride solution at high temperature might carry sufficient metal so that a fluid inclusion of the solution would on lowering of temperature precipitate a large enough crystal for microscopic detection.[33] Solutions of lower concentration and

[29] Hartley, W. N.: On the Presence of Liquid Carbon Dioxide in Mineral Cavities. Jour. Chem. Soc. (London) 29: 137–142, 1876; Julien, A. A.: On the Examination of Carbon Dioxide in the Fluid Cavities of Topaz. Jour. Am. Chem. Soc. 3: 41–43, 1881; Geissler, H., and Vogelsang, H.: Ueber die Natur der Flussigkeitseinschlusse in gewissen Mineralien. Pogg. Annals. 137: 56–75, 1869; Scharizer, R.: Zur Frage der Bildung der Einschlusse von flussigen Kohlendioxyden in Mineralien. Centr. Miner. Geol. 143–148, 1920.

[30] Hawes, G. W.: Liquid Carbon Dioxide in Smoky Quartz. Amer. Jour. Sci. 21: 203–209, 1881.

[31] Reese, C. L.: Petroleum Inclusions in Quartz Crystals. Jour. Amer. Chem. Soc. 20: 795–797, 1898. Davy, H.: Phil. Tran. Pt. 1: 367–376, 1822.

[32] Bastin, E. S.: The Fluorspar Deposits of Hardin and Pope Counties, Illinois. Ill. State Geol. Surv. Bull. 58: 64, 1931.

[33] Lindgren, W.: U. S. Geol. Surv. Prof. Paper 43: 213–218, 1905; Butler, B. S.. U. S. Geol. Surv. Prof. Paper 111: 358, 1920; Lindgren, W., and Whitehead, W. L.: *Op. cit.;* Sorby, and Butler, *Op. cit.*

trapped at lower temperature apparently precipitate amounts too small to be seen under the microscope.

Other solids mentioned are transparent rhombic shaped and prismatic crystals, the composition of which is not known.

Transparent, irregularly shaped masses are also reported in a few instances. Hydrogen sulphide has been identified by a number of writers, chiefly by odor. Unusual substances which have been reported from only one occurrence will not be considered.

FLUID INCLUSIONS IN SULPHIDES.[34]

Fluid inclusions are common in galena crystals that have grown on the walls of open veins, and may be as much as a centimeter in length but most of them are a millimeter or less in diameter. Some have also been found in sphalerite from several localities. Galena crystals from a number of sources were broken and the cleavage surfaces examined immediately under a binocular microscope, using strong oblique illumination. The brine from the cavities spreads on the fresh cleavage surface and on evaporation sodium chloride crystals form in parallel orientation with the galena.

Composition.—The cavities in most of the galena crystals are of such size and the solution is so concentrated that it is an easy matter to make qualitative microchemical analyses of the contents. The solution, spread on the cleavage surface outward from the cavity after breaking the crystal, tastes like sodium chloride. As evaporation progresses, crystals of sodium chloride quickly appear. Some of these were examined by the petrographic microscope and found to be isotropic. Final evaporation leaves a thin film of solution around each of the individual salt crystals, suggesting the presence of a deliquescent salt, which later tests have proven to be calcium chloride. The procedure used in microchemically testing these inclusions was as follows. After locating on a fresh cleavage surface an opened fluid cavity around which the solution has spread, the solution and its crystallizing salts (crystallizing due to evaporation) were taken up in a

[34] Based on work done by the writer.

drop of tested distilled water in a clean capillary tube. This was transferred to a glass slide and the analyses then carried out according to the procedure given by Chamot and Mason.[35]

Tests were made for Na, K, Ca, Mg, Cl, S, and SO_4 on all the material in the inclusions found. The details of the tests employed need not be given, but the kind of test used may be mentioned. Check tests against the reagents and against known elements, and against prepared combinations of different elements were made. The uranyl acetate test was used for sodium. This gives a very distinctive crystalline precipitate. Chloroplatinic acid was used on all samples to test for potassium, and on some, check tests were made with perchloric acid. Sulphuric acid was used to test for calcium. It gives crystals of $CaSO_4$, $2H_2O$ which have distinctive form and optical characters. Magnesium was tested for, using the sodium phosphate test. This element as well as potassium, where present in considerable proportion, may also be detected by uranyl acetate, which was used in making the sodium test. The resulting crystals are markedly different for the three elements. Chlorine was tested for by using silver nitrate; the resulting precipitate of silver chloride undergoes a characteristic color change when exposed to heat and light. Lead acetate and silver nitrate both failed to show any SO_4 present. The presence of S– in alkaline sulphides should have been detected in the silver nitrate test but none was found in any of the specimens examined. Very small amounts of SO_4 or S– would probably not be detected by the methods of analysis used. If present, CO_3 should also have been detected by the tests employed, but none was found. Liquid CO_2 if present would have escaped undetected. The tests where an element was found present were all strong and unmistakable. Solutions from cavities in Joplin and Leadville galena are neutral with litmus paper. Table I shows the results.

It will be seen that sodium and calcium chlorides are present in all the minerals examined, and that no other soluble constituents were found. This result was surprising and many special

[35] Chamot, E. M., and Mason, C. W.: Handbook of Chemical Microscopy, Vol. II. John Wiley & Sons, 1931.

TABLE I. SHOWING MINERALS EXAMINED AND THE ELEMENTS FOUND IN THE FLUID INCLUSIONS.*

X indicates Positive Test.

Mineral and Locality	Na	K	Ca	Mg	Cl
Galena: Single crystals					
Joplin, Mo.	×		×		×
Dubuque, Iowa	×		×		×
Galena, Ill.	×		×		×
Donnelley Mine, St. Francis Co., Mo.	×		×		×
Leadville, Colo.	×		×		×
Grange, N. J.	×		×		×
Weardale, Durham, Eng.	×		×		×
Glucks brunnen Mine, Siegerland, Westfalen	×		×		×
Salchendorf, Siegerland	×		×		×
Sonora, Mexico	×		×		×
Bleibuir, Mechernich, Eifel, Ger.	×		×		×
Freiberg, Saxony	×		×		×
Neudorf, Harz.	×		×		×
Mies, Bohemia	×		×		×
Egypt	×		×		×
Sphalerite: Single crystals					
Joplin, Mo.	×		×		×
Granby, Mo.	×		×		×
Echigo, Japan	×		×		×
Pico de Europa, Santander, Spain	×		×		×
	Secondary Fluid Inclusions				
Clausthal, Harz. Sphalerite vein wall crust	No tests positive except small amount Cl. Solution quite dilute.				

* Schertel, A.: Berg und Hütt. Zeitung, 1878, reports sodium chloride and zinc sulphate in fluid cavities in sphalerite from Spain. Strong reaction was obtained for Cl and weak one for sulphate. Sandberger, F. Von: Z. Krist. 19: 386, 1891, found sulphuric acid and Cl in sphalerite. Weber, J.: Z. Krist. 44: 223, 1908, found that where sphalerite from Santander, Spain was powdered, it gave off ammonium sulphide and hydrogen sulphide. It is not certain that these were derived from inclusions. Joplin galena, when broken, sometimes gives a slight fetid odor.

It is not known whether the inclusions examined by these writers were primary or secondary.

attempts were made to find other elements but without success. The check tests on mixtures of these elements in known proportions, however, indicate that where sodium is present in preponderant amounts, a small percentage of potassium or magnesium may not be detected. It is, therefore, possible that a

small percentage of these may be present. Calcium is present in much smaller amounts than sodium.

The spectroscopically determined [36] presence of sodium, potassium, or calcium in galena, sphalerite, pyrite and other sulphides from a number of localities is probably to be explained by the presence of these constituents in fluid inclusions, rather than in solid solution.

Concentration of Fluid Inclusions in Galena.—The solutions which were found in primary cavities are all concentrated. No appreciable difference in concentration could be detected in the solution from galena of one locality as compared with that of others. Attempts were made to estimate the concentration of sodium chloride present. By noting the relative amount of salt which crystallized out of a drop of the solution as compared with the size and thickness of the drop or film, a rough estimate was made. Also drops of solutions of sodium chloride of known concentration were placed on galena cleavage surfaces and the resulting evaporation of the solutions and crystallization of the salt was compared with that from the cavities. It is estimated by these means, which of course are only rough estimates, that the concentration is 12–25 grams of sodium chloride per 100 cc. of water.

Discussion of Results.—The primary liquid inclusions in the galena and sphalerite investigated are quite similar both in composition and concentration, in minerals from localities of widely differing geological relations. Since the solutions in galena from districts where ores were formed by igneous agencies are closely similar to that in galena from the Mississippi Valley type of deposit, it might be argued that all such ore-depositing solutions are magmatic in origin.

It seems to the writer, however, that an equally logical view is that galena is not carried and deposited in quantity unless the solutions are of this composition and concentration regardless of their origin.

[36] Hartley, W., and Ramage, H.: The Wide Dissemination of Some of the Rarer Elements, and the Mode of their Association in Common Ores and Minerals. Tr. Jour. Chem. Soc. 71: 533–547, 1897. Ammermann, E.: Neue Mineralvorkommen des Nordostlichen Westfalens. Centr. Min.: 578, 1924.

The theories that the upper Mississippi Valley deposits were formed by descending meteoric waters, or that the ores of the Tri-State district were formed by the weathering and concentration near the surface at the time of chert accumulation would seem to be definitely disproved by the nature of these inclusions. It is difficult to imagine that near-surface descending meteoric waters in rocks of the composition found in these areas would be as concentrated in sodium chloride as these enclosed solutions. They are in fact exceptionally concentrated for waters that are not derived from salt beds. If artesian circulation is appealed to, it would seem necessary to postulate rather special conditions, such as a newly opened circulation in which connate waters of special composition and concentration are being pushed upwards and out of the containing beds by incoming meteoric waters back at the artesian water source.

Connate waters closely similar in concentration and composition to these liquid inclusions have been found (outside of salt beds) in the edge waters of petroleum reservoirs.[37]

The fluid inclusions in galena are much more concentrated than the circulating waters to which Siebenthal[38] assigned a genetic rôle in the origin of the Joplin ores.

The solutions which formed veins were not of magma-like concentration *i.e.* containing several tens of per cent. of metals in solution. The very small amounts of opaque metallic substances that have been found crystallized from the solutions in fluid cavities of minerals indicate that at the most the heavy metals are soluble to the extent of only a few per cent. in ore-bearing solutions. Careful search was made for other minerals (solids) in numerous fluid cavities in galena and sphalerite but none were found. On the other hand, non-metallic constituents

[37] Newby, Torrey, et al: Bradford Oil Field: Structure of Typical American Oil Fields: II: 435, 1929; Levorsen, A. I.: Greater Seminole District, Okla. *Op. cit.*, II: 349; Gish and Carr: *Op. cit.* I: 189; Mills, R. Van A., and Wells, R. C.: The Evaporation and Concentration of Waters Associated with Petroleum and Natural Gas. U. S. Geol. Surv. Bull. 693, 1919.

[38] Siebenthal, C. E.: Spring Deposits at Sulphur Springs, Arkansas. ECON. GEOL. 9: 756–767, 1914; U. S. Geol. Surv. Bull. 606: 107–146, 1915.

in the solutions appear to range from ten per cent. up to several tens of per cent. of the solution.

GENETIC SIGNIFICANCE OF COMPOSITION OF FLUID INCLUSIONS

The presence of carbon dioxide and alkaline carbonates in the fluid cavities of quartz is doubtless of genetic significance. Aqueous solutions, particularly of the alkaline carbonates, have experimentally been proved to be good solvents of quartz.

All primary fluid inclusions found in the galena and sphalerite contain sodium chloride as the main substance held in solution. The common presence of sodium chloride in the fluid inclusions of these minerals strongly suggests a genetic relationship and that the metals are carried in chloride solutions.

This is in harmony with observations collected by Zies,[39] Clarke,[40] Lincoln,[41] Fenner,[42] and others on volcanic emanations and their effects.

The sulphides which were deposited in fumarolic crusts in the Valley of Ten Thousand Smokes appear to have been precipitated by hydrogen sulphide.[43]

This is a possibility to be considered in sulphide ore deposits, but the reaction with metallic chlorides tends to produce acid solutions. The fluids in cavities of galena tested by litmus paper do not appear to be acid. This is, of course, not a delicate test for acidity, but the abundant presence of carbonates in many lead and zinc ore deposits indicates that the acidity, if present, must have been very low. Although the elements may be very similar in fumaroles and in a locus of ore deposition at some depth in the earth's crust, the chemical reactions may well be quite different due to differing amounts of oxygen and pressure relations.

[39] Zies, E. G.: The Fumarolic Incrustations in the Valley of Ten Thousand Smokes. Nat. Geog. Soc., Katmai Ser. 1 (1): 157–179, 1929.

[40] Clarke, F. W.: The Data of Geochemistry. U. S. Geol. Surv. Bull. 770: 261–292, 1924.

[41] Lincoln, F. C.: Magmatic Emanations. Econ. Geol. 2: 258–274, 1907.

[42] Fenner, C. N.: The Katmai Magmatic Province. Jour. Geol. 34: 715–724, 1926.

[43] Zies: *Op. cit.*

Sodium chloride was the most abundant constituent held in solution in the primary fluid cavities in sulphides examined by the writer, but other workers have found sulphates in quartz and sphalerite. It is not known whether the inclusions found by other workers are primary or secondary. Evidence has been given by Butler [44] which strongly supports the idea that at times interchange of oxygen takes place from certain elements at high temperature to sulphur at lower temperature. Minerals containing the resulting sulphate radicle are present to some extent in many sulphide ore deposits. The fact remains that in the primary liquid inclusions in sulphides examined by the writer, no sulphate solutions were found and, if present, the radicle must form only a very small percentage of the solution.

Many geologists have held that the metals in solutions of magmatic origin are transported with alkaline sulphides such as sodium or potassium sulphide.

The reaction—

$$PbCl_2 + Na_2S \rightleftarrows 2NaCl + PbS$$

—suggested as a likely one going from left to right with falling temperature, would give the proper end products to account for the common association formed in the inclusions examined.

Some experiments made by the writer show that lead chloride and sodium sulphide in water will, when heated to about 275° C., form excellent crystals of galena. On the other side of the equation a solution of sodium chloride saturated at room temperature will strongly etch galena at 275° C. The time in each case was six days. The relative concentration of the several ions was different in the two experiments.[45]

[44] Butler, B. S.: Primary Sulphate Minerals in Ore Deposits. ECON. GEOL. 14: 581–609, 1919.

[45] Some solubility of galena in sodium chloride is indicated by a U. S. Patent process which proposes treating ores containing galena with a hot concentrated solution of sodium chloride "thereby dissolving the lead and silver in said galena in said hot salt solution."

SUMMARY AND CONCLUSIONS

Fluid inclusions are common in minerals and may be large enough and numerous enough so that their composition can be ascertained.

They afford probably the most exact evidence of any investigated on the composition and concentration of vein-depositing solutions. The writer hopes to have more exact quantitative analytical work done in this field.

Of the two kinds of fluid inclusions, primary and secondary, the first is of most interest from the viewpoint of mineral genesis.

It may be impossible to determine which of these two kinds of inclusions is present, but others may be positively distinguished. The ones in galena single crystals and in sphalerite single crystals, described in this paper, are without doubt of primary origin. Some fluid inclusions, clearly of secondary origin, developed along a sealed irregular fracture in a sphalerite vein wall crust, were found to be quite different from all the primary fluid inclusions examined from sphalerite and galena. The primary fluid inclusions represent samples of the mineral-depositing solutions. Most of the present known data on their composition and concentration is assembled in this paper. Sodium chloride appears to be one of the most abundant and widespread substances present, in the solutions held in cavities of minerals, especially in or adjacent to sulphide ore deposits. This compound is probably an essential part of most heavy metal-bearing solutions. It is suggested that the sulphides are carried in solution with sodium chloride and probably at higher temperatures with potassium chloride.

The concentration of sodium chloride in solutions found in galena and sphalerite from the Mississippi Valley type of ores excludes the possibility of formation by descending meteoric waters. Ordinary artesian waters such as have been emphasized by Siebenthal also seem to be excluded on the same basis. Judging by the fluid inclusions in galena and sphalerite specimens examined from a number of localities, a high concentration of sodium chloride is essential in the solutions which deposit large amounts of these ore

minerals. Such solutions were found in galena from localities in which the ores are related to igneous rocks, such as Leadville, Colorado, Freiberg, Germany, and others, as well as in the Mississippi valley type of ores.

It is concluded that the only known available sources for such concentrated solutions (outside of salt beds) are magmatic, and possibly the first artesian flow (connate waters) from newly tapped beds. Hence if lead and zinc ore deposits are ever formed entirely by artesian solutions they cannot form over a long period of geological time but are sharply limited to one segment of time in the structural and physiographic history of a region, i.e. the first part of artesian flow.

The quantitative amount of such modified connate solutions present in the artesian beds in comparison with the large quantity of ores in the Joplin region is an interesting subject for study.

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AN AID IN THE INTERPRETATION OF DIAMOND DRILL CORES.

EDWARD WISSER.

METAL mining companies use diamond drilling (or other forms of core drilling, such as shot drilling) largely in two ways. In the first way, known veins or other structures are explored at depth or along the strike. The holes are commonly short, and their interpretation is generally simple. This paper is not greatly concerned with this type of exploration.

In the second way, diamond drilling is used to explore little-known country where the initial chance for ore is not thought good enough to warrant the driving of crosscuts or other underground workings. In such cases conditions may differ greatly from those of the first type of exploration. The holes are often long and expensive. If one of these holes shows ore, or mineralization of promise, much may depend on the interpretation of the core. Extreme care is usually demanded, and a call made upon all the geologic knowledge that can be brought to bear upon the problem.

Whether the district be one of vein deposits, or of replacements in sedimentary rocks, the first and fundamental aid in drill hole interpretation is nearly always a thorough understanding of the structure. The grasp of structure should if possible be so firm that the drill core supplies merely a missing detail in the picture. Structure worked out from drill cores obviously requires a knowledge of the stratigraphy. Even in a region of veins, where stratigraphy in itself is often of minor importance, an important fault may be revealed in the core by a change of rock only.

Existing underground workings, or surface exposures, or both, usually form a direct aid in the interpretation of drill cores. A vein, for example, is cut in a drill hole. The strike is unknown, but it cannot fall within a certain arc, for if it did, the vein should have been cut in a certain long crosscut.

Where the drill core shows no ore, but does show mineralization or alteration, the significance, if any, of these should be known. The showings may indicate nearby ore, and if they do, it may be possible to say whether the ore lies above or below the showings. Such "ore guides," like knowledge of the structure, may be obtained only in well-known districts, and from long and careful study.

The above aids are fundamental. This paper describes a further aid. It has a limited application, but the writer has found it of value in diamond drill exploration in a region of veins.

The Intersection Chart (Fig. 1).—A drill hole of known bearing and inclination cuts a vein. The angle of intersection between the axis of the hole and the vein (the "core-vein angle") is measurable from the core. The vein may have any one of a number of attitudes, but in general these possible attitudes lie within certain definite limits as to dip and strike, and if either the dip or strike is (approximately) known, the possible attitudes are still further reduced.

If the strike of the vein is known, two possible dips, as a rule, correspond to a given core-vein angle. In the simplest case (Fig. 2-*A*), the strike of the vein is perpendicular to the bearing of the hole. The core-vein angle in this, and in all cases, is measured in a plane containing the hole and perpendicular to the plane of the vein. In this case if the core-vein angle (here measured in the plane of the paper) is 90° there is but one possible dip; it is obviously the complement of the angle of inclination of the hole. The maximum possible core-vein angle is of course in this case 90°. With a core-vein angle less than 90°, there are two possible dips, as shown in Fig. 2-*B* (Possible Veins 1 and 2).

In the general case, the bearing of the drill hole is not perpendicular to the strike of the vein, and the core-vein angle will always be less than 90°. (If it were 90° the bearing of the hole would be perpendicular to the strike of the vein.) Fig. 2-*C* shows the general case, with the vein strike and position of hole given. Two possible dips for a given core-vein angle ($\alpha = \alpha_1$) are shown (Possible Veins 1 and 2). Clearly, as the core-vein

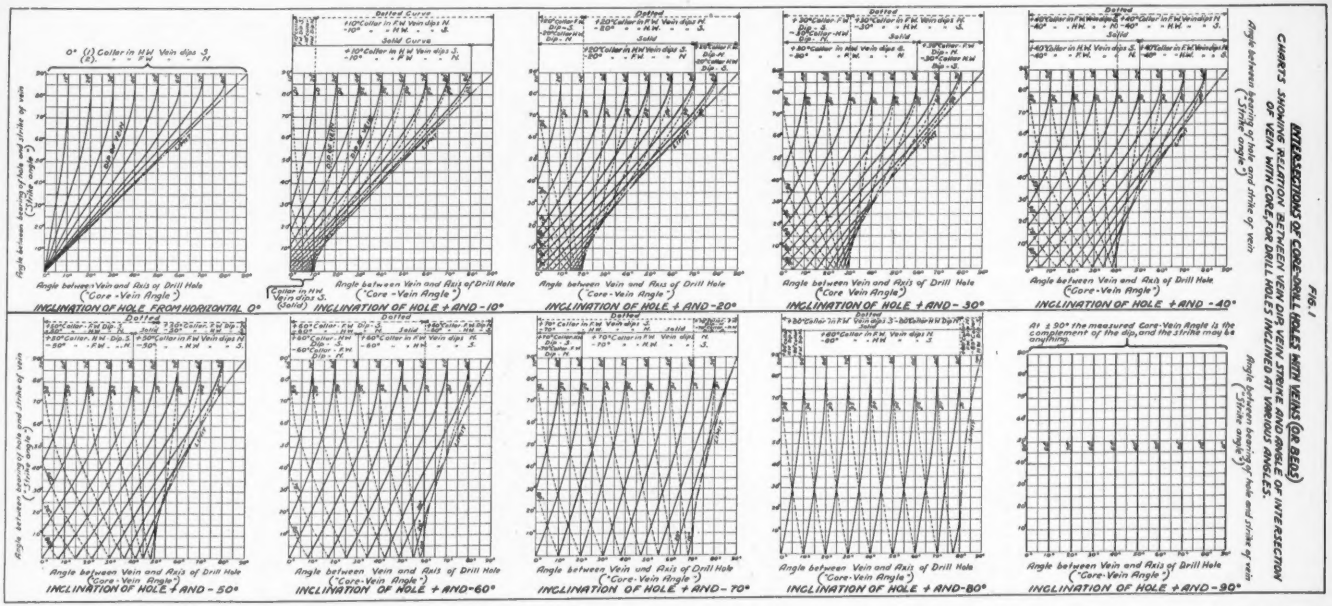
FIG. 1
CHARTS SHOWING RELATION BETWEEN VEIN DIP, VEIN STRIKE, AND ANGLE OF INTERSECTION OF VEIN WITH CORE, FOR DRILL HOLES INCLINED AT VARIOUS ANGLES.
INTERSECTIONS OF CORE-DRILL HOLES WITH VEINS (OR BEDS)
Angle between bearing of hole and strike of vein ("Strike angle")
Angle between Vein and Axis of Drill Hole ("Core-Vein Angle")
INCLINATION OF HOLE FROM HORIZONTAL 0°
INCLINATION OF HOLE + AND - 10°
INCLINATION OF HOLE + AND - 20°
INCLINATION OF HOLE + AND - 30°
INCLINATION OF HOLE + AND - 40°
INCLINATION OF HOLE + AND - 50°
INCLINATION OF HOLE + AND - 60°
INCLINATION OF HOLE + AND - 70°
INCLINATION OF HOLE + AND - 80°
INCLINATION OF HOLE + AND - 90°
Solid Curve
Dotted Curve
At ± 90° the measured Core-Vein Angle is the complement of the dip, and the strike may be anything.

FIG. 1. Intersections of Core Drill Holes with Veins (or Beds). Showing relation between vein dip, vein strike, and angle of intersection of vein with core, for drill holes inclined at various angles.

angle is increased, the planes representing the two possible dips will approach one another until they finally coincide. The core-vein angle at which the two planes coincide will be the maximum core-vein angle possible to obtain. Hence for this maximum core-vein angle there is only one possible dip for the vein. This

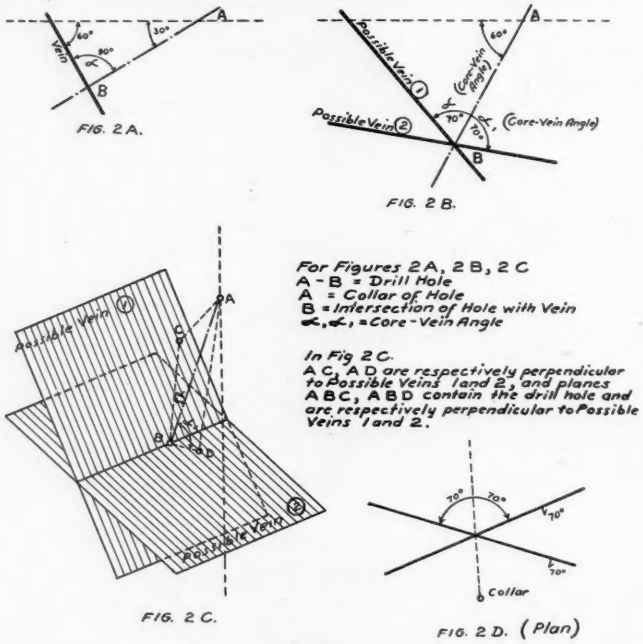

FIG. 2.

corresponds to the first case (bearing of hole perpendicular to strike of vein) where, with a maximum core-vein angle of 90°, only one possible dip for the vein exists.

Now consider the effect on the attitudes of Possible Veins 1 and 2 of increasing or decreasing the core-vein angle (vein strike constant). In Fig. 2-*B* the collar of the hole is in the hanging wall of Possible Vein 1, and the vein dips toward the collar of the hole

(*A*). Decreasing the core-vein angle from that shown in Fig. 2-*B*, increases the dip of the vein until a dip of 90° is reached. Further decrease in the core-vein angle causes the vein to dip in the opposite direction, so that now the collar of the hole is in the footwall, and the vein dips away from the collar. In Fig. 2-*B* the collar of the hole is in the hanging wall of Possible Vein 2, and the vein dips toward the collar. Decreasing the core-vein angle decreases the dip of Possible Vein 2, until a dip of 0° is reached. Further decrease in the core-vein angle causes Vein 2 to dip in the opposite direction, away from the collar of the hole. In this case the collar is still in the hanging wall.

Still referring to Fig. 2-*B*, increasing the core-vein angle of Possible Vein 1 causes the dip of the vein to decrease until the maximum core-vein angle (90°) is reached. The drill-hole is now perpendicular to the vein. Decreasing the core-vein angle from this maximum (always reading the smaller angle), causes the dip of the vein further to decrease. Possible Vein 1 has now become Possible Vein 2, for with decreasing core-vein angle its dip is now approaching 0°. Also, in Fig. 2-*B*, increasing the core-vein angle of Possible Vein 2 increases the dip until a maximum core-vein angle of 90° is reached. Decreasing the core-vein angle from this maximum causes the dip of the vein further to increase. Possible Vein 2 has become Possible Vein 1, for its dip is approaching 90° with decreasing core-vein angle.

Although the above relations are shown for the simplest case (bearing of hole perpendicular to strike of vein), they hold for the general case except that Possible Vein 1 passes into Possible Vein 2 at the maximum core-vein angle possible with the given strike of vein and position of hole, an angle less than 90°.

Where the dip is known (magnitude, and whether toward or away from the collar of the hole), there are in general two possible strikes. The veins in Fig. 2-*D* make the same angle of intersection with the drill core.

The charts (Fig. 1), for holes of various inclinations, show the two possible vein dips corresponding to a given core-vein angle and a given angle between bearing of hole and strike of vein

(" strike angle "). The solid set of dip curves shows Possible Vein 1 (Figs. 2-*B*, 2-*C*). The dotted curves show Possible Vein 2. The dips of Possible Vein 1 pass through a maximum of 90°, while those of Possible Vein 2 pass through a minimum of 0°, as explained above. One set of dip curves passes into the other at the line marked " Limit." This line is drawn through the maximum core-vein angles corresponding to various strike angles.

On the charts, the hole is taken as pointed north, and the vein as dipping north (whether N.W. or N.E., *i.e.* away from the collar of the hole), or south (whether S.W. or S.E., *i.e.* toward the collar of the hole). Notations above the solid and dotted sets of dip curves tell the position of the collar with respect to the vein, and the direction of dip of the vein (referred to a hole pointed north) as " Collar in H(angingwall)W(all,) Vein dips S."

When solving for the dip, given the strike and the core-vein angle, the smaller angle between bearing of hole and strike of vein is taken (" strike angle "), and the proper chart for the inclination of the hole is entered with this strike angle and the core-vein angle. The corresponding dips, with their direction, and the position of the collar, whether in hanging wall or footwall of the vein, are read directly. As the direction of the dip is referred to a hole pointed north, this is corrected to fit the actual bearing of the hole and the known strike of the vein.

When solving for the strike, the dip and core-vein angle being given, the strike angle is obtained from the charts, and the two possible strikes calculated or drawn from this angle and the bearing of the hole.

When the strike angle and dip are given, the core-vein angle is read directly from the charts.

Measurement of the Core-Vein Angle.—The use of the Intersection Chart depends entirely on ability to measure the core-vein (core-bed) angle. This angle is measured in a plane containing the axis of the drill hole, and perpendicular to the plane of the vein. Turn the core until the plane in the vein to be used in measuring the core-vein angle (either the vein wall, if well de-

fined, or some parallel streak in the vein) or the lamina in the case of beds, is in the position of Fig. 3-*A*, not that of Fig. 3-*B*. Measure angle "a" with a protractor. A straight-edge, of the same width as the thickness of the core, held along one side of the core, increases the accuracy of the measurement by representing the axis of the drill hole.

FIG. 3 A. FIG. 3 B.

FIG. 3.

Application of the Method.—The Intersection Chart may be used as an aid in drill core interpretation in districts where the structure of sediments is studied (replacement deposits in limestone and shale, for example), or in regions of veins, where the probable attitudes of veins cut in drill holes are desired. In general the attitude of sediments, owing to the frequent fissility of water-lain beds, can more often be deciphered by this method than can the attitudes of veins. Unless veins have sharp walls or banding, the core-vein angles cannot be read, even where the vein cores well. The core-vein angle of small stringers, however, can nearly always be read. Hence in districts where major veins have small parallel stringers in foot wall or hanging wall, a good guess as to the core-vein angle can often be made from these minor stringers.

For the proper interpretation of a drill hole, especially a long one, careful survey of the hole, for inclination and azimuth, is essential.

The examples given below are limited to veins, for the writer has not as yet used this method with sediments.

Example 1.—A hole inclined down at 30° bears S. 30° W. A vein is cut, making a core-vein angle of 40°. The prevailing strike of veins in the area is N. 70° E. (The "strike angle" is therefore 40°.) What is the probable dip of this vein?

Use the chart for Inclination of Hole — 30°. Strike angle is 40°; with a core-vein angle of 40°, the possible dips from the

chart are 80°, collar of hole in hanging wall, vein dipping S. (*i.e.* toward collar of hole) and 17°, collar in hanging wall, vein dipping S. Reducing to actual conditions, these dips become 80° N.W., and 17° N.W., since the vein strikes N. 70° E. and the hole points S.W. The 17° dip may be eliminated as too flat in most vein districts, hence the probable dip of the vein cut is 80° N.W.

Example 2.—A hole inclined down at 30° bears S. 30° W. It cuts a vein. The core-vein angle is 40°. The average dip of veins in the area is 70°, with a north component in the direction of dip. What is the probable strike?

Using the chart in Fig. 1 for Inclination of Hole — 30°, the dip curve of 70° (solid curve) under "Collar in HW, Vein Dips S." is selected, for this fits conditions reduced, as on the charts, to a hole pointed north. (In other words, the vein dips toward the collar of the hole.) With a core-vein angle of 40°, and this 70° dip curve, the strike angle is found to be 35° 30′. The hole bears S. 30° W. Laying off the strike angle on either side of this bearing gives probable strikes for the vein of N. 5° 30′ W. and N. 65° 30′ E. If the district is one of east-west rather than north-south veins, the N. 5° 30′ W. strike may be eliminated, and the probable strike is N. 65° 30′ E.

Example 3.—A vein strikes N. 80° W., and dips 70° N. It is desired to cut this vein by a hole inclined downward, the collar of the hole being in the hanging wall of the vein. The required bearing of the hole is S. 30° W., and the required core-vein angle is 50°. What should be the inclination of the hole?

Since the hole bears S. 30° W., and the vein strikes N. 80° W., the strike angle is 70°. A study of the charts with this and the core-vein angle of 50°, shows that the chart for inclination of hole — 60° gives a dip of 67° for the vein, and the chart for — 50° gives a dip of 77°. Interpolation gives an inclination of the hole of — 57°, to give the required core-vein angle with a vein dip of 70°.

Example 4.—A hole bears north, inclined downward at 20°. It cuts a vein. The core-vein angle is 65°. Nothing is known

as to the probable dip or strike of the vein. What are the limits for the dip and strike of this vein?

Examination of the chart for inclination of hole —20° with the core-vein angle of 65°, shows limits for the strike to be as follows: (*1*) An east-west strike (strike angle = 90°). The corresponding dip is 85° N. (*2*) A strike of N. 63° W. or N. 63° E. (strike angle = 63°). The corresponding dip is about 70° S. (The 70° dip curve runs very close to the line marked "Limit" and is not shown, but the dips on either side of the limit, 80°, solid, and 60° dotted, are shown.) The strike, then, may lie within the arc between east-west and N. 63° W., or within the arc between east-west and N. 63° E.

The limits for the dip are: (*1*) 85° N., corresponding to the east-west strike, and 45° S., also corresponding to an east-west strike. That is, the dip of the vein may vary from 85° N., through 90° to 45° S., each dip having a corresponding strike, in the N.W. or N.E. quadrant.

This is the "General Case" for problems of vein attitude. In practice, knowledge of regional strikes, or dips, or information supplied by existing mine workings or surface exposures, almost always cuts down the possible attitudes for the vein. (See Example 6.)

Example 5. (Figs. 4-*A*, 4-*B*). *Part 1.*—A vein on a certain level carried a stretch of ore (Fig. 4-*A*). A crosscut into the hanging wall north of the ore, affords an opportunity for cheap drilling below the ore, which is so far undeveloped below the level. Will a hole from the face of the crosscut cut the vein about 200′ below the level at a practical angle of intersection?

Draw vertical section *A–B* (Fig. 4-*B*), along the course of the proposed drill hole, using a chart or table [1] for projected dip to give the trace of the vein on the section. From the section, an inclination of the hole of — 40° will cut the vein 190′ below the level, with constant dip. The Intersection Chart (Fig. 1) for inclination of hole — 40°, with a dip of 70°, collar in hanging wall, vein dipping S. (*i.e.* toward collar of hole), and a strike angle of

[1] A good table is found in Lahee, Field Geology, 1923 Edition, p. 595.

54° (scaled from plan, Fig. 4-*A*), gives a core-vein angle of 53°, which should be satisfactory. From the section (Fig. 4-*B*) the vein should be cut about 300′ down the hole.

Part 2.—This hole is drilled. A vein is cut at 258′, and carries ore. Is this the vein sought? If the dip flattened from 70° to 60°, it could be the vein sought. (See Fig. 4-*B*.) In this case the core-vein angle should be 59°. (See intersection chart, with dip of 60° for the vein, other factors the same.) But the measured core-vein angle is only 25°. The Intersection Chart

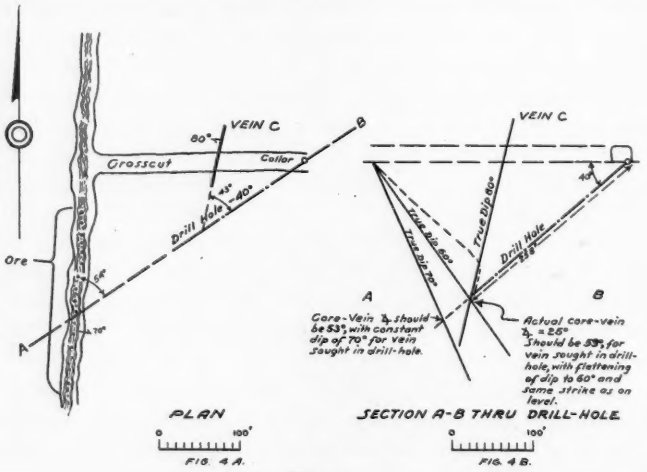

FIG. 4.

shows, for inclination of hole —40°, and a core-vein angle of 25°, that the only veins making this core-vein angle dip away from the collar of the hole ("north" on the chart). If this is the vein drilled for, and if the strike has not changed, then its position on the section must be that shown by the dashed line, Fig. 4-*B*. This is a scarcely possible contortion for most veins. A rather weak vein was found in the crosscut, Vein *C*, Figs. 4-*A*, 4-*B*. Its strike makes an angle of 43° with the bearing of the drill hole. The Intersection Chart (using core-vein angle of 25°,

strike angle of 43°, inclination of hole — 40°, collar in foot wall, vein dips away from collar, "north" on the chart), gives for this vein a dip of 80°. Hence the vein cut is probably Vein *C*, and the hole should be continued to the main vein.

Example 6. (Figs. 5-*A*, 5-*B*).—From Crosscut 500 West, 400′ Level, a drill hole is drilled S. 8° W. to the property line, at an inclination of — 30°. At point *B*, 100′ vertically below the 400′ Level, a vein is cut, making a core-vein angle of 66°. Within what area should this vein lie on the 600′ Level?

From the Intersection Chart (regardless, for the present, of modifying evidence from existing mine workings) it appears that for an inclination of the hole of — 30°, and for a core-vein angle of 66°, the collar of the hole is in the hanging wall of the vein, and the vein dips toward the collar ("south" on the chart). Also, from the chart, the maximum possible dip is 84°, the minimum 36°, and the strike angle lies between 61° and 90°.

From the mine workings, the vein strikes in the northwest quadrant, for one striking in the northeast quadrant would have been seen. For dips of every 10°, from 80° to 40° (roughly the maximum and minimum dips respectively), using the Intersection Chart, draw the corresponding strike lines through the point at which the vein was cut. These will be on the 500′ Level (100′ vertically below the 400′ Level). These lines are shown dashed in Fig. 5-*A*. Near Crosscut 50 West, project these strike lines up their respective dips to the 400′ Level, to get the position for the vein that would just be missed by 50 West Crosscut. The position with 80° dip would have been reached by the crosscut. That with 70° would not. Hence the strike line with 75°, just missing the south end of 50 West Crosscut, forms one limit for the area within which the vein must lie. The vein cannot dip more steeply than 75°.

Project the strike lines for the vein, with dips from 75° to 40°, down from the 500′ to the 600′ Level. The strike lines for 40° and 50° (these strike lines are all shown solid in Fig. 5-*A*), cross the west 600′ Level workings, and a vein with these attitudes should have been seen. Due to the "Limit" line on the charts,

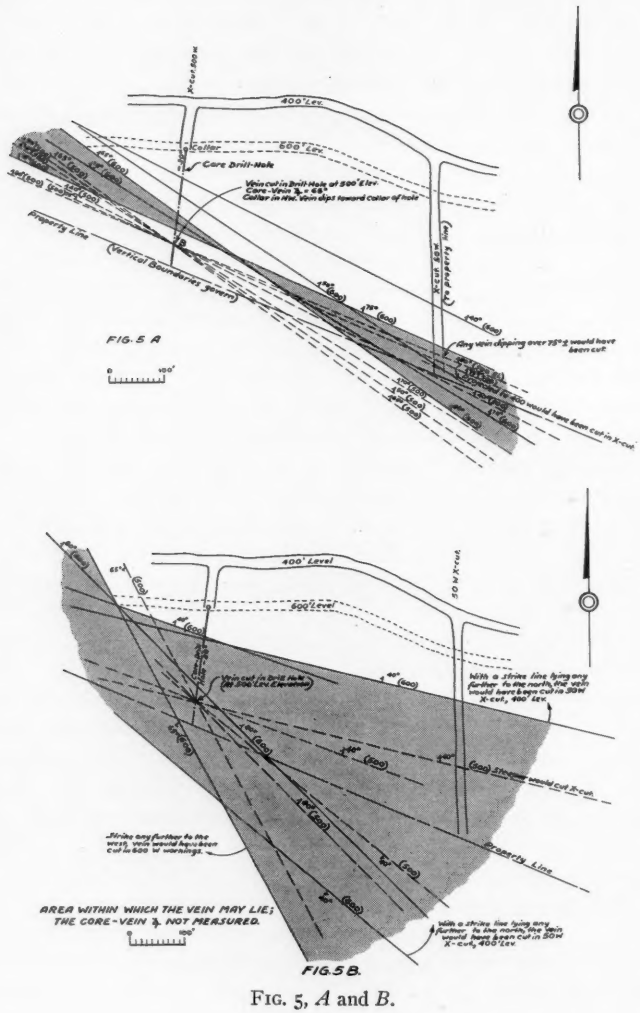
X-Cut 800 W
400' Lev.
Collar
600' Lev.
Core Drill-Hole
Vein cut in Drill-Hole at 600' Elev.
Core-Vein 3, = 45°
Collar in Hw. Vein dips toward collar of hole
Property Line
(Vertical Boundaries given)
X-Cut 50 W (To property line)
Any vein dipping over 75°-2 would have been cut
If vein dipping 75°-00 would have been cut in X-cut
FIG. 5 A
0
100'
400' Level
50 W X-cut
600' Level
Vein cut in Drill Hole at 600' Lev. Elevation
With a strike line lying any further to the north, the vein would have been cut in 50W X-cut, 400' Lev.
Strikes any further to the west, vein would have been cut in 600 W workings.
Property Line
AREA WITHIN WHICH THE VEIN MAY LIE; THE CORE-VEIN 3, NOT MEASURED.
With a strike line lying any further to the north, the vein would have been cut in 50W X-cut, 400' Lev.
FIG. 5 B.

FIG. 5, *A* and *B*.

the strike line with dip of 60° cannot be drawn. The strike line with dip of 70° does not cross the west workings. The strike line with dip of 65° just misses these workings, and hence forms the other limit to the area within which the vein must lie. This area is shown shaded in Fig. 5-*A*.

Compare this fairly concise solution with the case where the existing mine workings are the same, but the core-vein angle cannot be measured, or is not measured (Fig. 5-*B*). The area within which the vein may lie is much larger, for the vein might dip southwest, and hence, in a district where vertical boundaries hold, might lie largely outside of the company's ground.

General.—Vertical holes are often used in drilling for structure in regions of ore deposits in sedimentary rocks, where the deposits form along the beds. They are occasionally used in prospecting flat veins. In a vertical hole the core-vein (core-bed) angle is the complement of the dip, but there are no limitations to the possible strike, in contrast with inclined holes. (See Fig. 1, Inclination of Hole 90°.) Consequently, inclined holes will often tell considerably more of the structure than will vertical holes, and this may compensate for their increased length.

Acknowledgments.—The Intersection Chart was made by using a graphical solution for the core-vein angle, given the strike and dip of the vein and the bearing and inclination of the hole. The solution was based on the system of descriptive geology outlined by W. S. T. Smith.[2] The curves were checked by trigonometric formulae for the same problem derived by Mr. C. B. E. Douglas, mining engineer of Pachuca, Mexico. Further checking was done by the formulae for the dip, given strike, core-vein angle, and bearing and inclination of hole, in the *Mining Engineer's Handbook* (Peele, 1927 Ed., p. 398). These formulae are from an article by E. E. White.[3]

PACHUCA, MEXICO.

[2] "Some Graphic Methods for the Solution of Geologic Problems," ECON. GEOL., vol. 9, pp. 25–66, 136–152, 1914.

[3] Determination of Dip of Beds from Drill Cores, Eng. and Min. Jour., vol. 98, p. 254, 1914.

GEOLOGY OF THE ZINC–LEAD DEPOSITS AT PECOS, NEW MEXICO—PART II.

PHILIP KRIEGER.

CONTENTS.

Structural Features 450
The Shear Zone 451
Relation of Diabase Blocks to Structure 452
Structural Difference Between Evangeline and Katydid Ore Bodies 456
The Ore Deposits 460
Character of the Ore 460
Distribution of the Ore 465
Features Controlling Ore Deposition 466
Origin 467
Summary 468

STRUCTURAL FEATURES.

General.—The structural features of the Pecos Mine present a number of problems that appear to be of economic importance for carrying on a successful program of development and operation. Not only was localization of the ore largely controlled by the structural conditions existing at the time of ore deposition, but the size, grade and continuity of the ore bodies appear also to follow rather definite structural trends. The method of mining is almost entirely dependent upon the structural conditions within the shear zone. For these reasons, detailed mapping of the mine workings and a careful study of the existing structures are necessary.

It is by no means certain that all of these problems have been completely solved in the present work. Solutions have been arrived at, however, that seem to account satisfactorily for many of the features observed, and subsequent development, viewed in the light of these interpretations, appears to bear out most of the ideas concerning the structure. Additional development work

will, no doubt, throw further light on some of these problems.

The Shear Zone.—The shear zone in which the ore occurs strikes approximately north 45° east, and at the surface, it dips from 70° to 80° to the west. The maximum width of the sheared area is about 600 feet.

Numerous smaller areas in which shearing has taken place are exposed throughout the region. These conform, in general, to the direction of the main shear zone, but none have yet been found that showed evidence of mineralization similar to the larger one in which the mine is located. In the main zone of shearing local variations in the strike of the foliation may exist.

Within the area explored, the greatest intensity of shearing appears to have taken place along a major axis, with the development of parallel zones of lesser magnitude, but all being a part of a rather broad, general zone of deformation. The largest area of mineralization, in which is located the Evangeline ore body, occurs along a major axis of shear. The Katydid ore body is located parallel to the Evangeline, and about 200 feet to the west, occupying a shear zone similar to the Evangeline but of smaller size. What may represent a third zone [8a] containing ore mineralization was discovered during the summer of 1930 by diamond drilling from the lower levels of the mine. This is located approximately 300 feet east of the Evangeline ore body, and so far as could be determined from the evidence of two widely spaced drill holes, it likewise occupies a position approximately parallel to the major axis.

Movement evidently continued along the major axis during a greater part of the mineralization period. The ore within this area is distributed more irregularly, and replacement has not been so thorough as in the Katydid ore body. Post-mineralization movement is also more evident; the rocks are more broken and sheared, and patches of waste rock in the ore are more frequently encountered, making mining operations necessarily more selective.

In the Katydid zone replacement of the schistose rocks has been more complete and without the amount of movement during mineralization that characterizes the Evangeline ore body. The

[8a] Since proved to be the Evangeline shear zone [Editor].

ground does not tend to cave so readily; less timber is used and a cleaner ore is extracted.

Cross shearing in an east-west direction showing a small amount of mineralization has been encountered on some of the levels. In the northeastern part of the adit level the major shear turns to follow a direction almost due east. The same cross system of shear has been encountered in some of the crosscuts on this level, as well as on some of the lower levels. It has been followed toward the east for about 700 feet, but with the exception of small stringers of ore, no important mineralization has been found in it. It is thought that this shear eventually turns to follow the general northeast direction of the main shear zone, but there has not yet been sufficient development work done in this part of the mine to determine this.

Within the mine the dip of the foliation varies from 45 degrees to vertical. The most consistent dips, however, are from 75° to 80°. Above the 600 level the dips are all toward the west, but at about the 600 level they become nearly vertical, and below this point they change to 75°–80° E., then flatten to 40° E. just below the 900 level. This change in the direction of the dip has an important bearing on the ore mineralization and will be discussed more fully. Both the Evangeline and the Katydid ore bodies have a decided plunge toward the southwest. This can be best seen in the longitudinal section of the Evangeline ore body showing the areas that have been mined out (Fig. 10).

Relation of Massive Diabase Blocks to Structure.—Throughout the explored length of the shear zone there occur numerous massive, unsheared blocks or "horses" of diabase. They are commonly oval in shape and show evidence of intense shearing only around their outer margins. The rare mineralization in them is mostly confined to their outer margins or sheared portions.

These "horses" are believed to represent blocks of the diabase that have parted from the main mass along the joint planes, either during a pre-granite deformation or during the earlier stages of the deformation responsible for the present shear zone. Much of the granitic material penetrated around and between these blocks, isolating them from the main body of the dia-

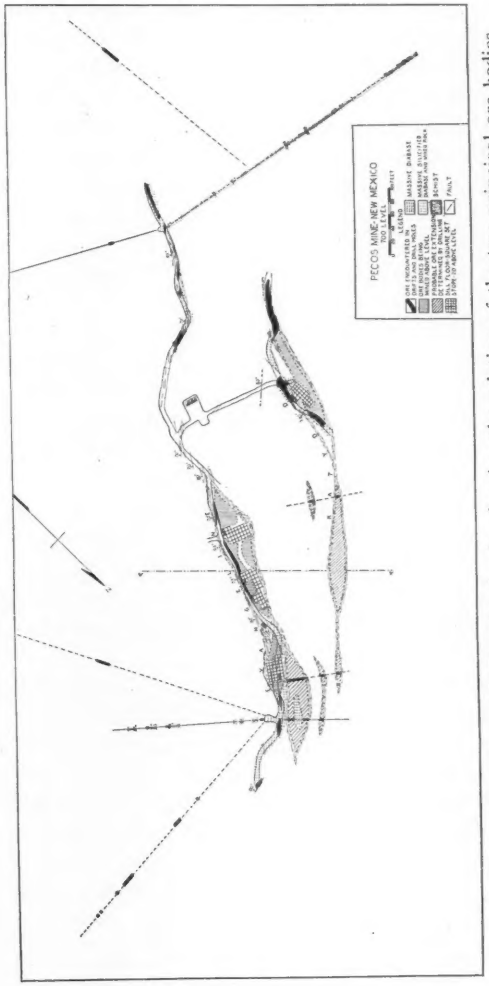

FIG. 9. Plan view of one of the mine levels, showing the relation of the two principal ore bodies.

base; some of it may have penetrated these areas without assimilating any great amount of the diabase. Other portions did accomplish some assimilation and reorganization of material. When movement took place, the granitic areas between the diabase blocks proved to be more susceptible to shearing than the more resistant diabase, so in these areas a mixed variety of schistose rocks were formed. The complexity of the sheared areas served at first to disguise successfully the true character of the rocks, but with the recognition of these features, their nature and occurrence may be easily explained. The diabase blocks had a tendency to divert the direction of shear, causing local variations within the zone of deformation.

These features can be seen throughout the length of the shear zone on almost any of the levels and are particularly prominent in some of the stopes where the schistose rocks have been replaced by ore minerals. In such places, massive sulphide ore shows the schistose structure of the rock which was replaced. Within the ore, large blocks or "horses" of massive diabase are found that exhibit no schistosity except around their outer margins, and have not been affected by ore mineralization. An examination of the antecedent structures preserved in the ore shows the schistosity going around the block and then continuing in the general northeast-southwest direction when beyond the influence of the more massive rock.

The influence of these diabase "horses" on the direction of shear is not confined to the horizontal direction only, but affects also the dip in a similar manner. Local changes in the dip are common, and in the case of the Evangeline ore body, the general direction of the dip of the shear zone and the ore has been reversed at about the 600 level. It is believed that the immediate area in which the change occurs may represent an area of the diabase that was not greatly broken before shearing took place; that the granitic material had penetrated only a narrow opening between two larger masses of diabase that acted as buttresses during the movement. Only a narrow area of schistose rock was developed here; one which was considerably tighter than most of

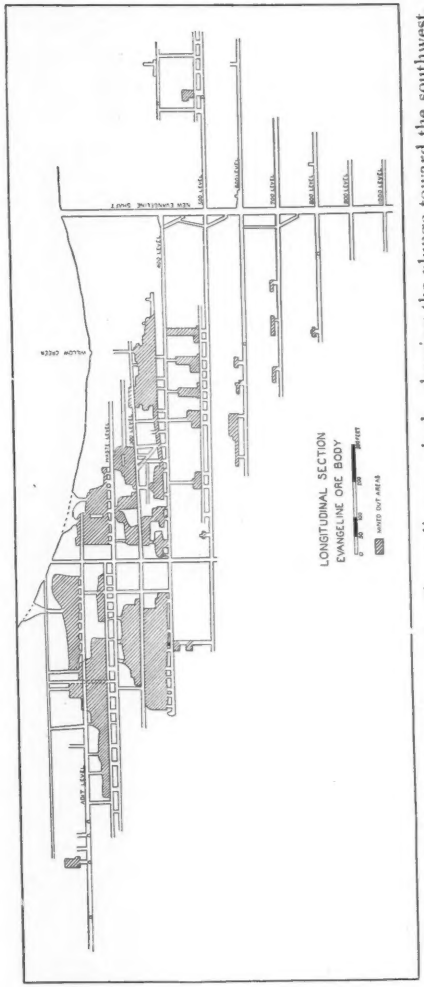

FIG. 10. Longitudinal section of the Evangeline ore body, showing the plunge toward the southwest.

the shear zone. For this reason mineralizing solutions did not penetrate so readily, or over so wide an area, and ore here occurs only in narrow stringers which are not of sufficient width to be worth mining. This condition is encountered on most of the 600 level except to the northeast of the main shaft, where the plunge of the ore body brings the tight area slightly above the level.

The recognition of the origin of these massive areas and their relation to the structure and mineralization is believed to be of importance in directing prospecting within the shear zone. In the stopes, the massive diabase blocks may completely cut off the ore for the width of the area being mined, but ore is apt to be found on their opposite side if the shearing has been directed completely around them. This feature was brought out in one of the stopes on the 600 level. The ore on the eastern side of the stope was cut off abruptly by an area of massive diabase, but in cutting through this, which proved to be about 30 feet wide, 25 feet of ore was encountered on the opposite side.

Structural Differences Between the Evangeline and the Katydid Ore Bodies.—Some outstanding differences between the Evangeline and the Katydid ore bodies are of significance because of their relation to the structure within the general zone of deformation. It was earlier stated that greater shearing is believed to have taken place along a major axis, the zone in which the Evangeline ore body occurs. This is manifested in the more broken character of the rock, and greater intensity of shear as well as post-mineralization movement. The economic importance lies in the fact that in the Evangeline zone, mineralization has taken place with a more patchy distribution, presumably because of the greater number of openings through which mineralizing solutions were able to penetrate. The Evangeline zone is also much broader than the Katydid, which, with the movement that undoubtedly accompanied mineralization, permitted easy access of solutions to a large number of smaller areas in which replacement took place. The diabase in this area is also thought to have been more finely broken or fractured, permitting entry to a greater quantity of granitic material and more extensive silicification of the diabase.

FIG.
bodies.

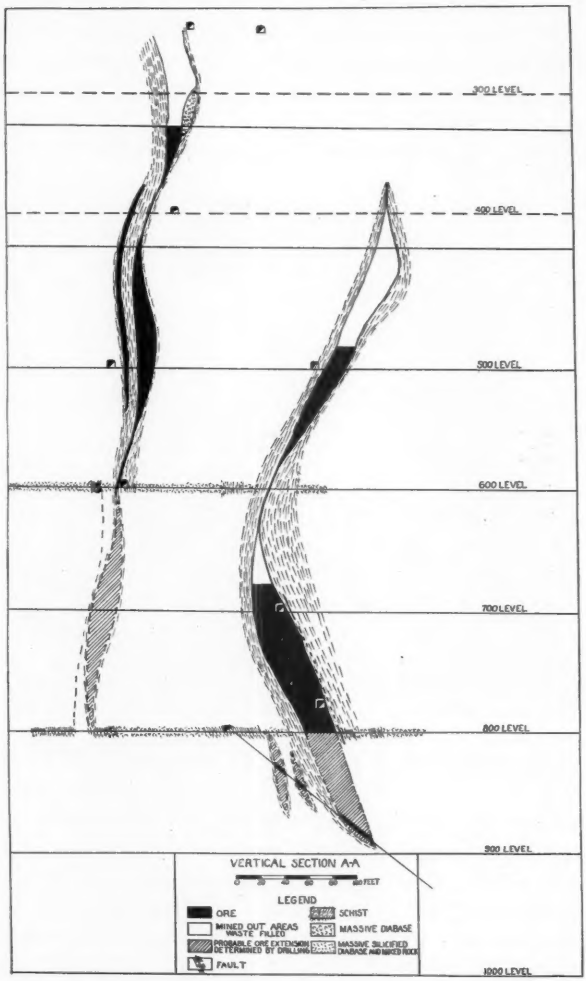

FIG. 11. Vertical section, showing the changes in dip of the two ore bodies.

That some post-mineralization movement took place within this zone is evidenced by the quantity of gouge found along the walls that commonly contains fragments of ore. A well-defined surface of post-mineral movement can be traced over several levels on the east side of the Evangeline ore body. Such movement as took place was probably distributed over a number of surfaces

FIG. 12. Xenoliths of the diabase broken along joint planes and caught up in the granite magma.

extending across the width of the Evangeline shear zone. The effect of such a movement would account for much of the waste rock with which the ore in this area is so intimately mixed.

Another feature of significance in the Evangeline ore body is that here one sees the most striking evidence of the selective replacement of schistose rocks rather than the wall rock by ore minerals. It is as though the solutions had freer access to more porous rock and were not confined long enough in one place to accomplish replacement of the wall rock.

These features are less prominent in the Katydid ore body. Replacement here has operated more extensively, and although the greater part of the mineralization occurs in the schistose rocks, the wall rock has been replaced also. The area is in general much smaller than the Evangeline, but there is not the dilution of ore due to the more irregular distribution that characterizes the Evangeline ore body. The mineralizing solutions that penetrated this zone were apparently confined to a smaller area, without the opportunity of distributing themselves through a large number of openings, or passing through with only slight replacement. In consequence, replacement was more thorough and even the wall rock was affected in some instances. This has materially aided mining operations in the Katydid ore body, as well as yielding a higher grade of ore per ton mined.

The Katydid ore body, in contrast to the Evangeline, has not been greatly affected by post-mineral movement. Its walls are commonly sharp and well defined. Both ore bodies carry considerable quantities of water. The porous and fractured nature of the Evangeline allows it to gradually seep away, and when water is encountered in this area by drill holes the pressure is not great. The Katydid area, on the other hand, appears to act as a reservoir for surface waters, and when encountered in drill holes the pressure is often sufficient to materially hinder the drilling operations.

What may prove to be a third zone of mineralization, occupying a position similar to the Katydid but on the opposite side of the Evangeline or major shear zone, was encountered in two drill holes from the 700 level. In plotting the position of this ore it was found to lie approximately 300 feet east of the Evangeline and 150 to 200 feet below the present workings of the Evangeline, that of the 800 level. From the evidence available at the time the field study was made this appeared to be another distinct zone of shearing and mineralization. Since then, however, development work has been extended to this depth in the vicinity of the main Evangeline shaft and exceedingly flat dips in the shear have been encountered. These appear to extend from the Evangeline zone to the new ore. In

this vicinity the new zone of shear has been proved to unite with the Evangeline, similar to the manner in which the Katydid zone approaches and appears to join the Evangeline in the northeast end of the mine. Although development on the lower levels at the present time has not progressed sufficiently to draw final conclusions regarding the structure on the lower levels, additional development should reveal some interesting features in this respect.

THE ORE DEPOSITS.

General.—Mineral deposits of sufficient size and grade to warrant mining are not abundant in the pre-Cambrian rocks of New Mexico; a few were mined in the early days. Most of these are now either entirely abandoned or are worked only intermittently as the price of metals rises or falls. The majority of these have been described by Lindgren, Graton and Gordon.[9] The Pecos district, according to available information, is the only one in which sufficient ore has been found to warrant mining on a large scale, and the only deposit of consequence belonging to a metallogenic epoch of pre-Cambrian age within the state.

Some mineralization has been found in the pre-Cambrian rocks just outside of the immediate vicinity of the Pecos Mine. The Johnny Jones property, a small prospect located about 6 miles southwest of the Pecos Mine, contains a small amount of sphalerite and chalcopyrite. The character of the mineralization and the rocks with which it is associated suggest an origin similar to that of the Pecos Mine; the property may belong to the same epoch of deformation and mineralization. A small amount of development work has been done on this property but there has been no appreciable production of ore.

Character of the Ore.—The ore of the Pecos Mine consists of sulphides of zinc, lead, and copper intimately mixed with pyrite and always associated with the schistose rocks which make up the greater part of the shear zone. A small but appreciable amount of gold and silver is also present. Pyrite is one of the most abundant of the minerals; so much so that it must first be

[9] *Op. cit.*

eliminated before a concentrate of the more valuable minerals is made. An average analysis of the ore has already been given.

The ore, like the rocks of the mine, is extremely variable. Some specimens contain practically all the major constituents, sphalerite, galena, chalcopyrite and pyrite closely associated with each other. In the majority, however, sphalerite and pyrite, the two most abundant constituents, are dominant. These were the earliest of the metallic minerals to form, the pyrite, in all cases, being the first. This was followed by the deposition of the sphalerite. Wherever these two minerals are observed together the sphalerite always replaces the pyrite, so there is no doubt as to the relations existing between them.

The pyrite commonly occurs in the form of cubes that vary in size from very minute dimensions up to one-half inch or more. It is the most persistent of the metallic minerals and forms large aggregates of crystals in the schistose rocks. The crystallizing power of this mineral is well illustrated near the outer margins of the more massive diabase "horses," where it also occurs in numerous isolated crystals of remarkably well-developed cubical forms embedded in the massive rock. Fractured crystals of pyrite are numerous and indicate recurrent movement during mineralization with later replacement by sphalerite along the fractures.

Two distinct varieties of sphalerite were found; the normal reddish-brown variety with the translucent optical behavior characteristic of sphalerite, and the black iron-bearing variety appearing in thin section as an opaque mineral and usually referred to as marmatite. Some idea as to the composition of the mineralizing solutions may be obtained from the relations existing between these two varieties. The reddish-brown variety was the earliest of these to form. During this stage of mineralization the solutions were evidently rich in zinc and deposition resulted in a nearly pure variety of sphalerite. During the later stages of deposition, however, the solutions appear to have been poorer in zinc and richer in iron, for the black marmatite surrounds the purer reddish-brown sphalerite. Analyses have shown the mar-

matite to carry as high as 15 per cent. of iron and to be considerably lower in zinc than the normal reddish-brown variety of sphalerite. Quite likely this relation between the zinc and iron is similar to that of many of the isomorphous compounds; the zinc and iron being interchangeable in the atomic structure of the mineral. This may account for some of the low zinc assays obtained on drill core samples that, to the eye, appear to carry more zinc than the assays indicate.

As both marmatite and the normal sphalerite reflect light by vertical illumination in the same manner, they are distinguished from each other with difficulty in a polished plate. In an ordinary thin section the marmatite and normal sphalerite are readily distinguishable; the marmatite appearing opaque whereas the normal sphalerite is reddish-brown and slightly translucent.

The sphalerite commonly occurs as massive bodies replacing the schistose rocks and the pyrite, and may be associated with galena and chalcopyrite. It may contain remnant crystals of pyrite, still showing a more or less cubical form, or the pyrite may be embayed and replaced by it. Sphalerite also contains numerous remnants of unreplaced chlorite, actinolite and sericite within it.

Both chalcopyrite and galena are later than the pyrite and sphalerite and replace the earlier formed minerals. The relation between the chalcopyrite and the galena, however, is less distinct; only one instance was observed where the galena occurs later than the chalcopyrite. The remainder of the specimens examined showed mutual boundaries between these minerals, and in view of the lack of definite evidence such as veinlets of the one mineral transecting the other, or residuals of one within the other, one is led to the conclusion that they were deposited contemporaneously, but definitely later than the pyrite and sphalerite. Slight overlapping may have occurred, with galena showing a tendency to be the later mineral.

Both chalcopyrite and galena occur in irregular masses disseminated through the sphalerite, pyrite and gangue minerals. A number of excellent examples of chalcopyrite replacing sphalerite along cleavage planes were observed in polished surfaces. One of these structures is shown in Fig. 16.

The chalcopyrite and galena also occur together in a number of stringers or veins, some of which cut the foliation of the schist. They probably represent the final stages of mineralization and penetrated the shear zone after most of the deformation had been accomplished.

Pyrrhotite occurs in subordinate amounts and is commonly associated with the earlier sulphide minerals, pyrite and sphalerite, and more rarely with chalcopyrite. Where it has been observed in contact with other minerals it replaces pyrite and sphalerite, but is replaced by chalcopyrite. Micro-chemical tests failed to show the presence of nickel.

Bornite was observed in only a few places; it is of no economic importance. It is associated with, and appears distinctly later than chalcopyrite.

Silver, in a ratio of about one ounce per ton to each percent of lead, occurs as small inclusions in galena and was seen only by etching on a polished plate. It is believed to be present in the form of argentite. Proustite has been reported but the writer was unable to identify it.

Common gangue minerals are quartz, chlorite, actinolite, sericite and tourmaline. The chlorite, actinolite, sericite and some of the quartz are products of recrystallization and alteration of the original rocks due to dynamic metamorphism and hydrothermal attack. Abundant quartz has also been introduced along with the ore minerals. The tourmaline is considered to have been one of the last minerals introduced, after most of the replacement by ore had been effected, but not before dynamic disturbance had completely subsided. The tourmaline crystals are mostly fractured and broken, but only one instance was noted where the fractures had been filled with sulphides. They probably represent the gaseous mineralizers of the crystallizing magma.

Oxidation and secondary enrichment are unimportant. Except for one stope in the upper levels, where a small quantity of secondary sulphides of copper was found, nothing that would indicate such a process was observed. An examination of the pre-Cambrian surface below the Pennsylvanian sediments showed that

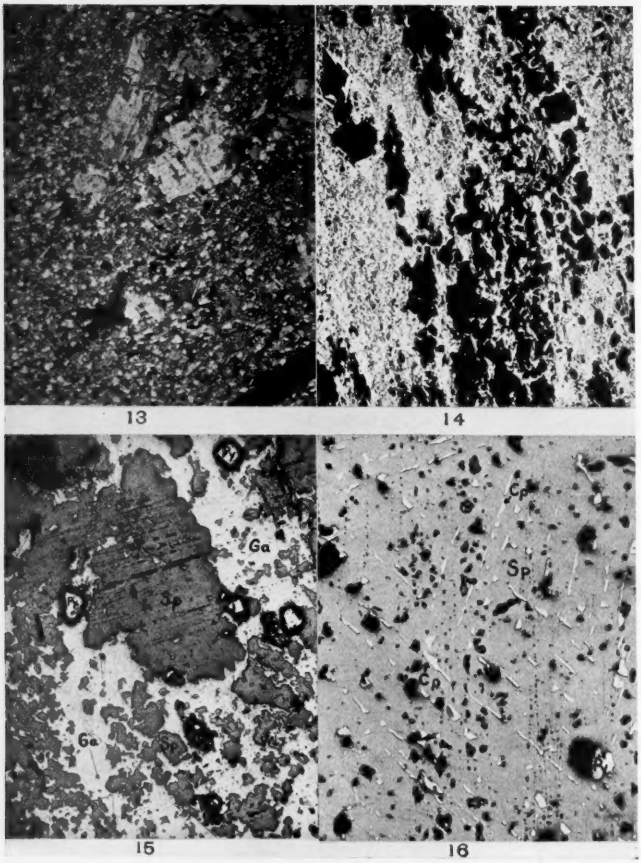

FIG. 13. Thin section of fine-grained schist, showing remnant crystals of feldspar partially crushed and recrystallized. × 15.

FIG. 14. Thin section of ore in schist. The black sulphides show the effect of movement along the plane of schistosity. × 15.

FIG. 15. Polished plate of ore, showing pyrite (*Py*) crystals partially replaced by sphalerite (*Sp*). Galena (*Ga*) replaces both pyrite and sphalerite. × 30.

FIG. 16. Polished plate of ore, showing replacement of sphalerite (*Sp*) by chalcopyrite (*Cp*) along cleavage planes. (This type of structure is interpreted by some as being due to unmixing from a solid solution. At the Pecos Mine, however, the evidence is of replacement and has been interpreted as such.) × 75.

oxidation had only penetrated a few feet, or if it did penetrate deeper, it was almost entirely eroded before deposition of the sediments. The fact that secondary enrichment is not an important factor in the mine would support the first view.

Distribution of the Ore.—Where almost complete replacement of the schistose rocks has taken place the ore occurs as massive bodies, lens-like in form, varying from 2 or 3 feet to 40 or 50 feet in width. This type of replacement has occurred throughout most of the two known zones of deformation. The individual ore bodies may taper at their ends to only narrow stringers, or mineralization may disappear entirely, and then widen out again along the strike of the shear zone. Lenses of ore also overlap each other, separated by areas of barren massive diabase showing intense silicification. A number of such lenses may be found along the strike of the shear zone on a single level.

The smaller lens-shaped ore bodies are particularly numerous in the Evangeline shear zone, where the individual masses of ore range up to a few feet in width and are commonly intimately mixed with gangue rock. This mixture of ore minerals with gangue rock is a characteristic feature of the Evangeline and is believed to have been brought about by recurrent movement along the major axis of shear during much of the period of mineralization. A number of these small lenses of ore may occur close to each other, separated by small areas of unmineralized material, but together forming a body of sufficient size and grade to warrant mining.

Ore minerals also occur as fine grains disseminated indiscriminately throughout the schistose rocks without forming a body of definite size or shape. Where such is the case it is usually found that movement has taken place after some of the mineralization was accomplished. Such movement did not take place along a single plane but appears to have been distributed over the width of the shear zone. Gouge is often found in these areas, carrying sulphide minerals that have been dragged along the planes of movement.

Another noticeable feature of the Evangeline ore body is the increase in content of lead, or of copper, on some of the lower levels

as compared with the content of these metals in the upper levels or in the Katydid ore body. The stringers or veinlets of quartz carrying galena and chalcopyrite may account for some of this increase but it is also believed to be related to the recurrent movement within the Evangeline shear zone. The chalcopyrite and galena, being the last of the principal ore minerals to form, would be expected to occur more abundantly in those areas where movement and deformation continued over a greater period of time, but ground that was not much broken or sheared subsequent to the deposition of pyrite and sphalerite, would be less likely to carry any great quantity of these later minerals.

In the Katydid ore body, where replacement has been more thorough, the ore is more massive and continuous without the mixture of gangue. This is particularly noticeable in the area above the 500 level southwest of the main shaft, where the ore was mined continuously over an area about 400 feet in length with only slight variations in width except in the upper portions of the body.

The same features observed along the strike of the ore bodies can be seen along the dip. That is, the individual lenses tend to narrow and pinch out and then widen again as depth is obtained. A plan view and a vertical section of the ore bodies brings out this feature.

The variation in size of the mineralized areas and the intimate mixture of ore with gangue, as in the Evangeline, make for a very irregular and patchy distribution of the ore.

Features Controlling Ore Deposition.—Although the mineralizing solutions are judged to have penetrated the shear zone with the more acid, end-stage concentration residuals of a granite magma, the ores themselves appear to show a distinct preference for the chloritic schists. The minerals most likely to form chlorite as an alteration product, such as hornblende, biotite and pyroxene, are almost entirely absent in the normal granite, but are abundant in the diabase and syntectic rocks. The abundance of chlorite in the quartz-chlorite schists, then, is judged to have been derived mainly from the ferro-magnesian minerals of the diabase. That these schists were not derived from the diabase alone is

evident from the large amount of quartz in them, which, even allowing for the liberation of silica by the alteration of feldspars, could not be entirely accounted for in this way. The most reasonable conclusion, then, is that these schists represent assimilation of diabasic rock by granitic material, which, on shearing, formed a quartz-chlorite schist that was readily attacked and replaced by ore-bearing solutions circulating through much the same channels as the granitic material which preceded it.

Ore is also found in the quartz-sericite schists, or those which were derived from more nearly normal granitic material. In this type of schist, however, ore is not nearly as abundant or of as high a grade as that found in the chlorite schists. Thus, it cannot be said that one rock has been responsible for ore deposition to the exclusion of others, but only that the chloritic schists have seemed to exert a greater influence on ore deposition than those made up mainly of quartz and sericite. It is quite possible that if assimilation of the diabase by granitic material had been greater in one part of the shear zone than in others, and shearing then produced a mixed quartz-chlorite schist, these would be the more favorable areas for ore deposition.

The character of the rock, then, has had some influence in the localization of the ore, although it may not have been the dominating influence. Undoubtedly, the structural conditions within the shear zone, permitting access to, and penetration by solutions, or confining them within small areas, were the major causes of localization. The weaker, crushed areas determined the direction of circulation, with replacement in this area occurring more readily in the chloritized rocks.

Origin.—The ore deposit at Pecos is considered to be of "primary" or hypogene origin. The minerals and their associations are largely characteristic of high-temperature, high-pressure deposits of late magmatic origin, classified by Lindgren as hypothermal deposits.

Solutions accompanied by gaseous mineralizers probably furnished the mode of transport for the metals. The solutions are believed to have originated as the final consolidation residuals of a granitic magma. Release of pressure, brought about by dy-

namic movement forming a wide shear or crushed zone, permitted the solutions to escape through the openings and weaknesses thus formed. In this zone they attacked and replaced the existing minerals of the schistose rocks. The presence of tourmaline, distributed throughout the mine, is evidence that gaseous constituents undoubtedly accompanied the mineralization. It is believed, however, that this material developed somewhat later than the principal metallic mineralization but before movement within the shear zone had completely subsided. Tourmaline is found with the sulphides. It is commonly broken and crushed, but only one instance was noted where the fractures in tourmaline were filled with metallic sulphides. This was with galena, one of the last of the metals to form.

The sequence of mineralization indicates that the earlier solutions to penetrate the shear zone were rich in iron and zinc. Later mineralization shows chalcopyrite and galena penetrating and replacing earlier formed minerals, and appearing in those areas where deformation continued over a longer period.

Recurrent movement within the shear zone probably affected both temperature and pressure so that some overlapping of mineralization occurred. In general, however, the temperatures are believed to have been gradually diminishing.

SUMMARY.

Ore deposition at the Pecos Mine is limited to crystalline pre-Cambrian rocks. These rocks form the underlying rock floor of the district and are exposed only along the canyons and river courses. The hills surrounding the Pecos Mine are mainly composed of overlying, slightly inclined, Pennsylvanian sediments.

The sequence of events leading up to the formation of the ore deposit is as follows:

The Diabase.—The earliest recognizable rock unit of the district is a diabase. This may have been intruded into older pre-Cambrian sediments that are now either entirely destroyed or concealed by overlying sediments.

Intrusion by the Granite.—During pre-Cambrian time the dia-

base was intruded by a granite that penetrated along earlier weaknesses and isolated blocks of diabase that had parted along fractures and joint planes. In some places much of the diabase was assimilated by the granite magma with the formation of syntectic products.

Formation of the Shear Zone.—As a result of the granite intrusion, and before final consolidation of the magma took place, shearing and intense crushing probably occurred along the same lines of weakness into which granitic material had earlier penetrated. This dynamic disturbance was sufficient to form a broad shear zone in which the greatest movement was taken up along at least two, and possibly three, distinct lines to form the Katydid, the Evangeline, and the Evangeline extension encountered during the summer of 1930. The greatest movement took place along the Evangeline and continued in this area for a greater time. The Katydid, and perhaps the new ore zone, probably represent sympathetic movements along a line approximately parallel to the Evangeline.

The isolated blocks of diabase within the shear zone were left as " horses " because movement took place more readily in the injected areas between them. The dynamic disturbance was sufficient to cause intense reorganization of the rocks within the shear zone, forming a variety of schists, some of them made almost entirely from the granitic material, others from the mixed granitic and diabasic material.

Introduction of Ore.—As consolidation of the granite magma proceeded, final concentration residuals resulted, consisting of acid solutions, water vapor and gases that carried sulphides of iron, zinc, copper and lead. Owing to the release of pressure brought about by shearing, these solutions and vapors penetrated the zone of weakness, forcing their way up through the sheared areas, replacing the schistose rocks through which they circulated. Slight movement continued even during deposition of the ore. Probably this occurred as a final readjustment of the almost completely consolidated granite magma, the solutions penetrating the shear zone as long as openings existed.

Replacement appears to have been somewhat selective; chloritic schists being the more favorable, though not sufficiently so as to exclude replacement in other rocks. The largest ore bodies and the richest ores occur intimately associated with the chloritic minerals. In some instances the diabase wall rock is replaced, principally in the Katydid, where it is believed that the solutions were more confined than in the Evangeline. Control of deposition, however, is essentially structural, and the character of the rock acts as a minor secondary control.

The ore minerals consist of pyrite, sphalerite, galena and chalcopyrite with a minor amount of pyrrhotite. All these minerals are of primary, late magmatic origin. Secondary enrichment is negligible. The individual lenses of ore are distributed irregularly throughout the shear zone and vary in size from a few inches in width to 40 or 50 feet. They are all elongated, lens-shaped bodies, aligned in the direction of shear.

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PROSPECTING FOR "OIL" IN AUSTRALIA AND NEW GUINEA. PART II.

E. C. ANDREWS.

CONTINENTAL STRUCTURES AND "OIL" DEPOSITS.

Unequal distribution of "Coal" and "Oil" Deposits in Northern and Southern Hemispheres.

If now the geologic and economic significance of the results supplied in Part I be sought, some light would appear to be gained by a reference, on the one hand, to the known distribution of the main coal and oil reserves of the world and, on the other hand, to the great continental structures with which they are associated.

Coal Reserves.—The "actual" and "probable" coal reserves of the world, as estimated by the International Geological Congress of 1913, with appropriate modifications for the Southern Hemisphere, and for Russian Europe, in view of more recent information, appear to be, approximately, as follows:

	Millions of Tons
North America	5,050,000
Europe [17]	1,250,000
Asia	About 1,300,000
Australia and Oceania	35,000
Africa	58,000
South America	32,000
Total	7,725,000

An analysis of these figures, even on the assumption that no uniform method of estimate has been adopted, indicates the marked disparity existing between the tonnage of coal reserves of the Northern and Southern Hemispheres, the latter containing less than two per cent of the World's known reserves and Australia itself less than half of one per cent. It may be noted

[17] Inclusive of large additions recently announced by Russian Survey.

also that the North American reserves comprise about two-thirds of the total, Europe and Asia each an amount exceeding 15 per cent., whereas the reserves of Africa, South America, and Australia, individually, are almost negligible by comparison.

"Oil" Reserves.—A consideration of the known "oil" reserves of the world reveals an even more remarkable lack of uniformity in distribution. Furthermore, the continents that contain the main reserves of coal, so far as known, also possess those of "oil," whether on the mainland proper or considered together with the island arcs associated with them.

Thus about 83 to 85 per cent. of the known "oil" reserves of the world is obtained from that part of America lying north of the equator, while the second producer in order of importance is that geographical and geological unit which may be called Greater Europe (including Russia, Persia, Mesopotamia, Armenia, and Turkey), while smaller amounts are obtained from South America south of the equator, Greater India including Burma, and the main island arcs and festoons associated with Eastern Asia and Australia, which junction to form the Malay Archipelago. The continental areas of South Africa and of Australia do not appear to have produced commercial pools of "oil" to date.

The amount of prospecting for mineral deposits already carried out in the Southern Hemisphere, together with the success generally attending such work, indicates definitely that there is something beyond chance in this failure to find coal and "oil" fields in the Southern Hemisphere comparable with the famous examples of the Northern Hemisphere. It matters not, in this connection, whether an explanation is sought in the distribution of Northern and Southern plant and animal life during the various periods of coal and "oil" formation, or in the assumption that the southern lands were larger during past geological periods, the fact remains that the great bulk of the known reserves of coal and "oil" occur in the Northern Hemisphere.

So soon, however, as a geological map of the world is consulted, a definite association is noted to exist between geological structure and the main coal and oil occurrences, whereby, so far as

investigations have proceeded to date, less than two per cent. of the coal and oil [18] reserves have been located within the Southern Hemisphere.

In the first place, it will be noted that the continents of the Northern Hemisphere are larger than those of the Southern Hemisphere, the latter tapering off characteristically to the south. Antarctica is an "oldermass" [19] in great measure, concerning which we possess only scanty information at present. The Wegener hypothesis is an attempt to explain the present peculiar disposition of the continents, together with their general form. It, however, does not appear to be supported by a study of the major continental structures, nor by the known distribution of the great commercial deposits of minerals such as coal and oil. Whatever agencies have been at work in the assemblage or concentration of the main coal and oil deposits, the fact remains that prospecting operations, past and present, indicate the practical monopoly of these minerals by the Northern Hemisphere. Moreover, great as is this discrepancy in regard to coal distribution, it is still more emphasised with respect to oil. With the exception of

(1) South America, whose structure as described below is homologous with that of North America, Europe and Greater India, and

(2) The East, or Netherland, Indies, and New Guinea, which belong as much to Northern, as to Southern Hemisphere structures,

the oil supplies of the Southern Hemisphere are almost negligible.

From the point of view of general structure, it may be seen that the major land blocks, such as North and South America, Greater Europe, and Asia, consist of nuclei of ancient rocks, which, on the one hand, are encircled in great measure by subconcentric, or festooned, rings or zones of other very old but possibly less ancient rocks and, on the other hand, are associated,

[18] Excluding Java and Sumatra, which lie within an island arc near the equator.

[19] Term proposed by W. M. Davis for relatively stable masses forming a base or foundation for the associated younger less-altered sediments, or other rock types.

over limited areas, with broad unstable zones of Tertiary and later Mesozoic, the latter having trends somewhat sympathetic with the general marginal strike of the rocks composing the more ancient inliers. The Cordilleran and Alpine areas containing the younger and less stable mountain types, such as the Greater Himalaya, The Alps, The Andes, and the North American Cordillera, form integral [20] portions of the continents themselves. Within the continental basins or troughs separating these outer zones from the ancient nuclei, the great stores of coal and oil have been assembled. The outer troughs associated with the Tertiary and post-Tertiary Cordilleran areas also contain oil (or coal) deposits. North America and Europe are the ideal examples illustrating these conditions, but Greater India and South America form less ideal examples. China, with Japan, is a still less ideal example.

A slight elaboration of this general statement may, perhaps, be advisable at this stage.

North America.—This large continental mass already, in the pre-Cambrian, was present in skeleton form,[21] consisting of a nucleus known as the Canadian Shield, and a compound ring or belt of land roughly harmonizing in trend with the present peripheral area of the continent. Of these two elements the nucleus is the older and is overlapped and surrounded by irregular zones, including both late pre-Cambrian and Paleozoic sediments, apparently dipping off the Shield in all directions so far as examined.[22] To the North of the Shield, as also in eastern Canada,

[20] Exceptions in some measure to this grouping are the island arcs and festoons of the Caribbean Area, of Eastern and Southeastern Asia, and of Northern and Eastern Australia, where the younger mountains merely approach (Australia) or actually touch (America and Asia) the mainland.

[21] For a general discussion of the Paleogeography of North America see C. Schuchert, Pres. Address, Geological Society of America, 1923, pp. 151–229. The evidence adduced by Schuchert (and Walcott as quoted by Schuchert) indicates that North America was actually larger, during one portion at least of pre-Cambrian time, than it is at present. At that time, however, it was not the stable structure that it is to-day.

[22] Hudson Bay appears to be the revival of a structural depression of great antiquity with rocks of the late pre-Cambrian and of Paleozoic age dipping from the Shield and into the depression.

the Appalachian Region, the Southern States, and the Pacific Province, younger belts of land occur, in which stability by folding was attained during the Paleozoic, for the northern, eastern, and southern portions. Permanence and stability of the area were effected in stages, but the work of American and Canadian geologists indicates that the activities towards the close of the Paleozoic Era were responsible, in great measure, for the strengthening of the Eastern portion of Canada and the United States. The Pacific, with the Central American and Caribbean Provinces, have been relatively mobile until the present time, especially on their sea-ward aspect.

In a general way, it may be stated that stability was extended from the outer rings towards the Shield, although the folding and thrusting were directed also towards the neighboring oceans.

The relative stability, which was progressively developed in saltatory manner, resulted in the formation of the present continent of North America, in which an enormous, but compound structural trough, separates the Shield proper from the strongly compressed Paleozoic sediments to the east and south. Troughs closely related to this main example were developed on the sea-ward aspect of the Pacific Cordillera, and also between Paleozoic fold lines of the Southern States and the Caribbean-Greater Antillean arcs. Within this ideal compound structural trough are included the greatest coal and oil fields of the world so far as prospecting operations have revealed to date.

Greater Europe.—Europe, from a structural point of view, includes the Scandinavian massif as its main ancient nucleus, and its boundary on the east passes through the Urals, the Caspian-Aral Area, and the Afghanistan-Baluchistan-Persian boundary, while the southern portion is bounded by the Gulf of Persia, the Arabian massif and the Mediterranean.

A consideration of this land block reveals a definite homology with North American tectonics, but, as a structural unit, it is not as simple and perfect.

The nucleus of the continent is Fennoscandia, which formerly was co-extensive with a large portion of the British Isles. Associated with the Shield, and lying in part northwards of it, are

older Paleozoic rocks with the main axis of their fold thrusts arranged subparallel to the marginal areas of the ancient nucleus. Fold lines of the older Paleozoic also appear to pass through the Urals and the area south of the nucleus, but stability there, in the main, was accomplished during the later Paleozoic. Another series of fold lines belonging to the later Paleozoic Age, traverses the British Isles and the western portion of Europe, and possibly joins the Ural lines to the south of the European Plain. The outer or Alpine area, extending from Spain to Persia, was affected by these movements but, as with the Pacific Cordilleran belt of America, it has remained more or less a mobile and unstable area to the present day. Between this unstable [23] Alpine stretch and the Shield to the North lies the Great European Plain and Basin.

Partly within this Basin and the related structures within the British Isles, and partly also within the Basin's southern extension and the compound Alpine zone, lies the second of the great coal and oil fields of the world.

Thus it may be noted that, in Europe as in North America, the coal and oil basins are not simple, but compound, the Alpine belt being associated on each side with structures containing either coal or oil deposits, or both.

South America.—South America, with its Brazilian-Orinocan nucleus, and its outer Andean Chain, together with the outer Caribbean belt of mobile and unstable island and mountain ranges, exhibits a definite similarity of structure with North America and with Europe. So also Greater India with its Peninsular nucleus of ancient rocks underlying the Paleozoic types and surrounded to the west, north, and east, by arcuate and unstable structures, known as the Baluchistan, Suleiman, Himalayan, and Burmese, mountain ranges.

In each of the two countries described in the preceding paragraphs, the unstable arcs are separated from the stable nucleus by broad compound troughs, some of which the sea has entered at various times. In others, structural troughs occur in the form of intermontane valleys. In each of these again natural oil occurs in considerable quantities.

[23] Both the Alpine and Cordilleran (American) zones include old stable inliers.

In the case of Australia, the " oldermass " or nucleus is formed by the main block comprising Western Australia, South Australia, Central Australia, and Northern Australia (Northern Territory). From this ancient metamorphic complex, large areas of Paleozoic, and even of so-called pre-Cambrian sediments dip gently, with very few exceptions, a well-known example of such exception being the long, narrow belt extending northwards from Adelaide towards Lake Eyre, where thick masses of Cambrian rocks were strongly compressed apparently during the earlier Paleozoic Era.

Eastern Australia became relatively stable during the Paleozoic, the stability being attained progressively throughout the era by compressive movements, whose effectiveness passed away in directions generally east and north with the passage of time. The outer unstable zone is represented by the East Indies, New Guinea, New Britain, New Ireland, the Solomons, New Zealand, and other island groups. The outer basin separating the island arcs from the mainland is a great double structure hinged at Torres Straits, comprising the Arafura, Coral, and Tasman Seas. The compound structure separating the ancient massif of Australia, west of the 142d Meridian, from the Eastern Australian highlands, consists of the Great Australian Artesian Basin of Queensland, New South Wales, and South Australia in the north, and the Murray Basin in the south.

The main axis of the structure is meridional while its main boundaries consist of the continental fringe of highlands, varying from 2000 to 7300 ft. in height on the east with the relatively low lying Shield to the west.

The Eastern Australian margin, which varies from one hundred to three hundred miles in width, has been practically free from strong compressive movements since the Paleozoic, whereas the southern and southeastern portions have not suffered marked compression since the closing Devonian. Mesozoic sediments occur plentifully in this area but have not suffered severely from folding and metamorphic activities such as have profoundly affected the pre-Permian types. This Paleozoic belt corresponds, apparently, with the Ural, Hercynian, and some other lines in Europe, and with the Appalachian, Southern States, and Arctic

belts of North America. Like them also it contains inliers of rocks which have been profoundly altered and which are in part early Paleozoic, and in part also possibly late pre-Cambrian in age.

The outer arcs of mobile islands correspond to the Cordilleran (or Andean), Caribbean and Antillean arcs, for North and South America; to the broad and compound Alpine zone for Europe, to the Baluchistan, Himalayan and Burmese arcs for India and to the island festoons of Eastern and South Eastern Asia.

All other things being equal, we might then expect to find oil deposits both in the Great Basins of the Australian Mainland and also in the basin separating the island arcs from the mainland, provided the great troughs are occupied by the right types of sediments and that their sediments have been unaffected by strong folding or by marked metamorphism, as in the magnificent examples of North America, Greater Europe, India, and some other countries.

These arcs, however, are not yet an integral portion of the continent of Australia. Moreover, the Tertiary Marine sediments of Eastern Australia have been warped well below sea level during the progressive movement westward of the axis of uplift which affected Eastern Australia in Tertiary and post-Tertiary time. These facts appear to explain, in great measure, the failure hitherto to discover a great continental oil field on the eastern margin of Australia such as is found in the Gulf and Mexican regions for North America and the Venezuelan and Colombian regions for South America.

If attention be directed now to the double basin separating the ancient nucleus, or nuclei, of Western and Northern Australia from the Paleozoic strip of Eastern Australia, it will be found that this structure presents some general points of similarity with the great inner basins of North America and of Europe. Several points of difference, however, may be noted at this stage of the discussion:

(1) The main inland basins of North America and South America and of Europe are larger than the Inland Basin of Australia.

(2) The great inland basins of North America, South America, Europe

and Greater India are bounded, on one side at least, by high unstable mountain ranges, whereas the main inland basin of Australia is not bounded on any side by Alpine or high Cordilleran types.

(3) Paleozoic sediments on the margins of each are strongly folded, but in an area such as North America, the Paleozoic members, including the Cambrian, lie subhorizontally or at least with gentle folds on the southern aspect of the Canadian Shield and to the west of the Appalachian Valley.

Sediments of Lower Paleozoic age and even of supposedly late pre-Cambrian age, dip gently off the Australian nucleus; nevertheless in Eastern Australia, with rare local exceptions, the sediments of pre-Permian age have been strongly folded and, in the majority of examples, they exhibit marked alteration or metamorphism.

(4) The rocks occupying the Great Australian Artesian Basin comprise Mesozoic, Tertiary, and post-Tertiary sediments, and igneous rocks with a minor development of Permian on the east and the southeast, the beds passing with undulations into the Basin.

(5) The sediments occupying the Basin itself do not pass gradually from highly folded marginal members on the east into sub-horizontal and gentle rolling types towards the nucleus.

(6) The Great Artesian Basin appears to have existed as a broad shallow trough during the Mesozoic and Tertiary periods, and there is no evidence of the existence of a long-enduring mobile geosyncline within it, although the locus of maximum deposition appears to have wandered from one side to the other of the basin during the Mesozoic Era. Neither is there any evidence of the existence of a high mobile geanticline forming the eastern boundary of the basin during Mesozoic and Tertiary time. On the other hand it is noted that in almost all oil fields which are associated with what may be called the Tertiary and post-Tertiary arcs or zones of instability, the oil deposits appear to be closely related in some manner or other to sediments that have been deposited in geosynclines, as the term is used by Schuchert,[24] and subsequently folded strongly along the margins, the effect dying away gradually with increase of distance from the main axis of the trough.

These points are considered in the succeeding pages, but before dealing with them in detail it may be noted that, as a rule, the great oil deposits of the world favor earth movements which have

[24] Site and Nature of the North American Geosynclines. Pres. Address, Geol. Soc. of America, 1923, pp. 151–229.

resulted neither in remarkably high ranges, nor in ranges of marked Alpine type. Among notable examples of the latter may be mentioned the Alps proper, the Andes of Chile, Peru, and Ecuador, the Himalaya proper, the Hindu Kush, the Kuenluen, the Thian Shan, the Alai and Trans Alai, which are not associated with large and important oil fields, whereas the great oil fields of the world, namely, those of the United States, Canada, Mexico, Venezuela, Roumania, Mesopotamia, Persia, Turkey, and so on, are associated with plateaux of moderate to considerable height rather than with true Alpine or Himalayan types. To this statement the Caucasian fields may be considered to form an exception, but the mountain structure there appears to be much more remarkable in type and limited in width than the Andean, Himalayan and higher Alpine types.

Returning to the consideration of the Great Australian Artesian, and Murray Basins, it may be noted that:

(*a*) The Permian sediments occur in great thickness at various points to the immediate east of the Great Basin, but these sediments do not appear to have any marked extension westward in the Basin itself.

(*b*) Mesozoic sediments are weli represented [25] within and around the Australian Artesian Basin, but have not been recorded for the Murray Basin.

Mesozoic Sediments.—E. J. Kenny, while conducting the Underground Water Survey of the Trans-Darling area in New South Wales, found the thickness of the Jurassic sediments to vary from 200–400 ft. of fresh water beds of highly porous nature. R. L. Jack records the maximum thickness of the Jurassic

[25] Reid, J. H.: The Marginal Formations of the Great Artesian Basin in Queensland. Fifth Inter-state Conference on Artesian Water, Sydney, 1925, pp. 30–32 inclusive. By authority.

The information contained generally in several Artesian Reports issued by the States is of the greatest value to students of the several inland basins of Australia.

Jack, R. L.: Geol. Surv. So. Australia, Bull. 14.

Jensen, H. I.: Geological Reconnaissance between Roma . . . and Tambo Queensland Geol. Surv., Pub. No. 277, 1926, pp. 1–216. By authority.

Kenny, E. J.: West Darling District (with map). Dept. Mines, N. S. W., Ann. Rpt., 1930, pp. 81–82.

beds in South Australia as 800 ft. H. I. Jensen, in dealing with the Mesozoic and Tertiary rocks in the Carnarvon area (including Roma), supplies the following approximate estimates of thickness.

	Ft.
Marine Cretaceous	+ 2000
Walloon (Jurassic)	
Upper Walloon (with coal)	
Orallo Coal Measures	
Big Sandstone	5000
Culcairn (Injune formation)	
Basal Sandstone	
Bundamba (Upper Trias)	Between 3000 and 5000
Ipswich (Middle Trias)	4000
Clematis Sandstone (Permo-Trias)	2200

Jensen records a very great thickness of Permian rocks underlying, or associated with, this Mesozoic development.

The western portion of the Basin contains Cretaceous and Jurassic sediments, the maximum recorded thickness of the Cretaceous being 2800 ft. within the State of New South Wales, and alongside the Queensland border. The Jurassic of the Northwestern portion of New South Wales varies from 200–400 ft., and its maximum recorded thickness, according to Jack, is about 800 ft.

From an analysis by Kenny of the many hundreds of deep bores which have been sunk within the Basin, it would appear that the deepest bores occur along a line lying a little to the east of the center of the Basin proper, and a line connecting these deep bores, which vary from 5000 to 7000 ft. in depth, is approximately parallel to the eastern margin of the Basin. In this portion of the Basin are developed the Winton (or fresh water) Measures with a maximum thickness of 3000 ft. These beds are younger than the other Mesozoic rocks described below.

The Jurassic is thus seen definitely to thin towards the west. The marine Cretaceous attains its maximum apparently in the western portion of the Basin, and the Winton beds appear to be confined to the more central portion of the Great Basin.

Tertiary and Post Tertiary Rocks.—These are relatively thin and are limited apparently to fresh water types.

During the Tertiary Period, apparently Miocene, a great amount of surface silicification was effected. A dense skin of secondary "quartzite" was developed thus over extensive sandy tracts of the Basin, the extreme thickness observed by the writer and E. J. Kenny being about 20 ft., as at the White Cliffs Opal Field, New South Wales. An average thickness is probably 4 to 5 ft. Various local names, such as "Grey Billy," "Desert Sandstone," "Shin-cracker," and "Geyser" have been given to this formation.

During the Kosciusko Period [26] (apparently closing Pliocene) the low-lying surface of erosion occupying the eastern portion of Australia was warped to form the present Eastern Highlands, culminating in the Kosciusko Plateau, 7300 ft. in height. The movement was accomplished in stages, the larger streams maintaining their courses against the uplift. The sediments of the Great Artesian Basin were warped into gentle structures during this period, as is admirably shown by the various low plateaus and fault-scarps within, or alongside of, the Basin and by the undulating form given to the "Grey Billy" layer which rises above the plain in gentle, but irregular, anticlines and domes with troughs between these low crests, as shown by boring conducted for artesian water.

Kenny reports the existence of buried "Grey Billy" at depths ranging to 100 ft. below the surface of the present plain. In the elevated areas the "Grey Billy" has suffered so much from denudation that, in many places, it survives only as cappings to flat-topped outliers of Jurassic or Cretaceous sediments.

The Murray Basin appears to be filled with Tertiary and post-Tertiary Sediments, the Tertiary being Marine and the post-Tertiary mainly fluviatile. The maximum recorded thickness of these formations, as recorded by boring, is 2100 ft. The thicker portions of the sediments occur in the western portion of the Basin.

[26] Andrews, E. C.: Geographical Unity of Eastern Australia. Proc. Roy. Soc. N. S. W., 1910, p. 426.

These two divisions of the main inland Basin appear to have had different histories, that of the northern one extending from the Permian onwards, the other being formed during Tertiary and post-Tertiary, so far as information is available.

The Great Artesian Basin itself is a compound structure, discharging, in part, to the Gulf of Carpentaria in the north, and to the Lake Eyre Basin in the south or southwest.

A vast number of natural discharges occur throughout the whole of the southwestern marginal areas of the Basin and also against inliers located within the southern and western portions, the general fall being from the highlands of Queensland and New South Wales to the southwest and west respectively. The traveling waters of the deeper portions of the Basin are essentially of carbonate as distinct from sulphate, or chloride, types.

No authentic surface sign of oil has been detected associated with these natural discharges of the Basin.

Many hundreds of bores, varying from 1000 to 7000 feet in depth, have been sunk in the Great Basin for artesian supplies. Of these, the Roma bore discharged gas in abundance, as mentioned under the note on the prospects in Queensland. As a result of this discharge many bores have been sunk at Roma, and at Longreach also, in search for oil, but no commercial success has been achieved to the present.

In view of the fact that "wet" gas (with oil prospects also) has been found during boring operations within the Greater Roma District, both at Roma and Longreach, it is considered by some investigators that large oil deposits have been entrapped in these localities by structures formed during the Kosciusko Period, whereas the artesian water itself is conceived as flowing underground from the intake beds to the "mound" springs, or other natural discharges, in Western Queensland, New South Wales, and northeastern South Australia.

No undoubted sign of petroleum, however, has been recorded from any one of these hundreds of natural outlets from the Basin. Moreover, the compound structure of the Great Artesian and Murray Basins exceeds 700,000 square miles in area, and, in other parts of the world, any very large tract of oil-bearing country, say

from 500,000 to 1,000,000 square miles in area, has possessed certain valuable surface indications which, in turn, have led to the development, not only of the locality in the vicinity of the surface signs, but also to the prospecting of other, possibly, "hidden" fields in the same great extent of territory. This is the conclusion to be drawn from a study of the history of the prospecting and development of the oil industry in New Guinea and New Zealand in the Australasian Region; in Pennsylvania and other States situated in the eastern portion of North America; in Kansas and Oklahoma, and so on, for the Mid-Continental field; and in Mexico, California and Alberta, for Western North America. A similar statement applies also to Venezuela, Colombia, Russia, Roumania, France, the Caucasian Region, Persia, and Burma. Even in the Argentine, where the Comodoro Rivadavia field is reported to have been discovered accidentally by the drilling of a Government well for water, it may be noted that:

(1) The whole Argentine Province between the 20th and 50th parallels of south latitude, and the 60th and 70th meridians of west longitude does not exceed the area of the combined Great Artesian and Murray Basins, nevertheless, many surface indications of oil have been noted along the eastern front of the Andean Chain.

(2) Although no surface indications were observed at Comodoro Rivadavia itself, nevertheless "at a point 60 to 70 miles West and North of Comodoro Rivadavia, Rio Chico, near Lake Conles Whapi, several large asphaltic seepages are reported." [27]

(3) One or two bores sunk for water at Rivadavia are reported to have revealed oil in abundance without special precautions having been taken to ensure rising of the oil to the surface. In Australia it is commonly stated that the failure of the many hundreds of Artesian bores to reveal the existence of commercial oil deposits lies in the fact that special precautions have not been taken to allow oil and gas to rise against the head of water encountered.

(4) The occurrence of oil deposits in the Argentine appears to be directly or indirectly associated with the existence of the great Andean Chain which forms an integral portion of the continent in this region. In Australia, on the other hand, there is no equivalent,

[27] Clapp, F. G.: The Occurrence of Petroleum. Handbook of Petroleum Industry, Vol. 1, 1922, p. 150. John Wiley and Sons.

or homologue, of the Andean Chain closer than the outlying island arc comprising New Zealand, New Caledonia, and New Guinea.

CONCLUSIONS.

The evidence adduced in the foregoing notes tends to endorse the statement of F. G. Clapp [28] in 1926: "It would be folly to assume that no deposit of commercial oil exists anywhere on the Continent" [Australia].

Furthermore, each Government of Australia, whether Federal or State, is keenly alive to its responsibilities in the matter of investigating reported "finds" of oil and dealing with each case individually on its merits, as it arises.

A single instance of the form this assistance takes may be cited. Thus, at the present time, and at the request of the Commonwealth Government, the geophysicist [29] to the Geological Survey of New South Wales is laying out a magnetometric survey on certain structures in the Mount Gambier (South Australia) and Gippsland (Victoria) Districts, which have been reported upon favorably by the geological advisers to the private interests concerned.

Nevertheless, even with the hope always held out that, somewhere or other on the mainland, commercial supplies of oil may yet be found, it is felt to-day as in 1924,[30] that if commercial supplies of natural oil do occur within the continent, then there must be much more difficulty in the location of such than was experienced in the cases of the great commercial deposits of other countries. The prospectors of Australia, during the period 1851 to 1900, both knew and carried out their work as well as did any large body of prospectors elsewhere. Their methods may have been crude, but they were powerful and effective, being directed with rare common sense. Nevertheless, the same crude prospecting methods which have led elsewhere to the discovery of the greatest oil fields of the world have not sufficed to locate com-

[28] The Oil Problem in Western Australia. ECON. GEOL., vol. 21, p. 410, 1926.

[29] J. M. Rayner.

[30] Andrews, E. C.: Prospecting for Oil in Australia. ECON. GEOL., pp. 157–168 1926.

mercial oil deposits in Australia. The explanation of this failure to date is the main theme of the present paper.

This suggests, in turn, that oil fields in Australia, if discovered hereafter, may be of commercial dimensions, but cannot well be expected to be among the great ones of the world, for, if the artesian water of the Great Basin is under such head that it burst through in a myriad places, one may well expect the entrapped oil of "gushers" to have given some indication at the surface of their presence in this enormous Basin.

DEPARTMENT OF MINES,
SYDNEY, N. S. W.,
AUSTRALIA.

DISCUSSION AND COMMUNICATIONS

SECONDARY CONCENTRATION OF LAKE SUPERIOR IRON ORES.

Sir: The article by John W. Gruner [1] appearing in your March–April number contains a number of misstatements about basic field data.

After a series of references to known igneous or hydrothermal deposits outside of the Lake Superior region and bearing little or no relation to Lake Superior conditions, Mr. Gruner passes to the point where he makes the misstatements of fact to which the writer desires especially to call attention.

On page 196, referring to the possible relation of ores to ancient erosional surfaces, he makes the statement that there is but one instance in the Lake Superior region where the conformable slates overlying the iron formations have been removed by erosion and a later series substituted for them.

> In most cases there is no indication whatsoever that an ancient erosion surface was closer to the soft ores than the present surface. Practically always, slates were deposited on the iron formations conformably. These slates were not removed by erosion except in the case described below.

He then goes on with a brief and incomplete description of the well known Eastern Gogebic occurrence where pre-Keweenawan erosion has resulted in the substitution of Keweenawan formations for the upper part of the Ironwood iron formation and the overlying Tyler slate. He states that the point where ore occurs nearest to the Keweenawan basal erosion surface is 100 feet from it. This is true for the sketch cross section which he introduces, which is evidently located between the Brotherton shaft and the east boundary of the Brotherton property. However, he ignores the fact that less than a quarter of a mile to the east, in Sunday

[1] ECON. GEOL., vol. 27, pp. 189–205.

Lake property, an important soft ore body is directly in contact with the basal Keweenawan erosion surface. Here locally a pre-Keweenawan river channel cut through the lean upper part of the iron formation, which elsewhere lies against the Keweenawan, and cut into the favorable horizons in which most of the ore is found. Along this channel, pebbles of concentrated ore and well oxidized iron formation occur above and in direct contact with the ore and oxidized formation below the unconformity. Some of the conglomerate was mined as ore. In other words, the reason for non-existence of ore along the basal Keweenawan unconformity through most of its length is the unfavorable character of the iron formation at the contact. Where the contact bites deeply into the iron formation and cuts through the overlying lean refractory horizons, ore concentration does occur in important quantity, and the ore pebbles in the conglomerate show that much of this concentration took place before the outpouring of the Keweenawan lavas.

In stating that this one instance at the Brotherton and vicinity is the only case where the conformable slate above the iron formation has been removed, Mr. Gruner ignores the entire Eastern Menominee Range, where the Hanbury slate has been proven in the field to be unconformable on top of the Vulcan iron formation, and where only fragmentary and occasional occurrences of the conformable Loretto slate survive beneath the Hanbury slate.

He also overlooks the entire Marquette Range, in which not one occurrence of whatever conformable slate may once have been laid down above the Negaunee iron formation survives. Along every foot of some seventy-five miles of the entire main trough of the Marquette Range and its branches, the Negaunee iron formation is truncated by the basal unconformity of the Upper Huronian Goodrich quartzite and Michigamme slate series, the truncation being at its deepest in the western portion of the range, where little of the Negaunee iron-bearing member remains, and at its shallowest at Ishpeming, where probably some 3500 feet thickness of the Negaunee member remains with its top truncated by the Goodrich unconformity and no sign whatever of any con-

formable slate. That this pre-Goodrich period of erosion and weathering produced profound oxidation and leaching of the Negaunee iron formation and resulted in important ore bodies which were then evidently soft and were later specularized by subsequent heating and pressure, is shown by probably the most spectacular field evidence which exists of weathering on an ancient and long-vanished land surface. This ancient unconformity is throughout the Marquette Range the locus of hard ores entirely without regard to the immediate presence of igneous rocks. On the other hand, numerous soft ore bodies on the Marquette occur in direct contact with igneous intrusions. In fact, as on the Gogebic, the field evidence is that iron ore is found in structural troughs with relatively impervious bottoms and characterized by communication either with the present or with an ancient erosion surface. Igneous rocks on the Gogebic commonly form one element in the production of structural troughs. On the Marquette the structural troughs are produced frequently by folding and occasionally by the intersection of dikes with these folds. On the Eastern Menominee the troughs are produced by faults and by drag folds, and not one igneous rock has been identified in an intensive search of the main range of the Eastern Menominee by generations of geologists. In the entire Upper Huronian series of the Western Menominee Range, within which all the high-phosphorus ores of this district are included, but three dikes have been found. One of these dikes in conjunction with a fold structure forms a trough and apparently has some influence upon the concentration of ore, but it is interesting to observe that not one sign of specular hematite has appeared in the Upper Huronian in this district and most of the ore bodies are many miles from any known dike.

It is further interesting to note that there is not one iota of field evidence in the Lake Superior district to connect the formation of ore with contact effect of an igneous intrusion or with hydrothermal solution emanating from such an intrusion. The main producing portion of the Mesabi Range is notably lacking in igneous intrusion. Where the great gabbro laccolith of the Western Gogebic achieves important size and approaches the iron

formation, the formation is found to be refractory, magnetic, amphibolized, wholly unamenable to the ordinary weathering processes of concentration, and no ore has been found. The same is true where the corresponding Duluth gabbro mass approaches the Eastern Mesabi Range. All evidences of concentration and important commercial ore bodies are wanting on the Eastern Mesabi. Yet, if Mr. Gruner's theory is to be given weight, the Western Gogebic and the Eastern Mesabi should be a miners' paradise. The ore formation exists in full width and of as good iron content as unconcentrated iron formation elsewhere in the same district, yet not one commercial ore body exists with these igneous relationships which should, according to Gruner's hypothesis, create an ideal set-up.

The Cuyuna Range, like the high-phosphorus ores of Iron County, Michigan, exists in a terraine notably devoid of igneous activity subsequent to the deposition of the iron formation.

On the Gogebic Range itself the weight of evidence is that the entire Tyler series is unconformable upon the Ironwood iron-bearing formation and that such conformable slates as may exist at the top of the iron formation are at best only fragmentary.

It is a curious fact that specular hematite is seldom or never found in the Upper Huronian iron formations of Michigan. Specular hematite is frequently found in the Middle Huronian, and where it is so found the evidence of post-Middle and pre-Upper Huronian oxidation is always good, and the amount of specularite found seems closely proportional to the degree to which such pre-Upper Huronian weathering proceeded before the laying down of the Upper Huronian put an end to that weathering cycle. On the west end of the Mesabi, where there seems to be evidence of removal of the Upper members of the iron formation, specular hematite is found more abundantly than elsewhere on the Mesabi Range. That the Mesabi Range corresponds to the Middle Huronian of Michigan seems highly likely from its bed by bed correspondence with the Gogebic Range, whose Middle Huronian age has been definitely proved in the field. This question is not especially related to the problem of igneous ore origin except in so far as it indicates a correspondence with Michigan conditions

where the specular hematites are confined to formations older than Upper Huronian and are definitely referable to pre-Upper Huronian weathering.

These facts as to ancient weathering have been developed through generations of work by field men some of whom are still at work and many of whom leave names and contributions which will be authoritative for generations to come. As against this weight of field evidence collected by generations of careful investigators, Mr. Gruner makes a categorical statement that the Brotherton occurrence near the base of the Keweenawan is the only instance where an ancient erosion surface has approached as close to the ores as the present erosion surface or has removed the overlying conformable slate. In this case he states that there is no evidence of this ancient erosion surface having contributed to the concentration of ore. In order to make this statement he has had to select a cross section about a quarter of a mile west of a point where there is every field evidence of the concentration of important ore on and by this very same ancient erosion surface.

Mr. Gruner has in the laboratory shown that certain iron minerals can be produced from certain other iron minerals by hydrothermal processes under controlled conditions. This is interesting and to some extent confirmatory of the already observed facts regarding the specularizing of ancient soft ores. That such a laboratory process necessarily duplicates nature is no more indicated than that any one of the many thousands of laboratory and commercial synthetic processes necessarily duplicates the course of nature.

Whatever the merits of Gruner's idea from a laboratory standpoint, the field evidence of concentration of Lake Superior iron ores by downward oxidizing waters along circulation channels provided by folds, faults, dike intersections, or other structural channels, and related to present or ancient land surfaces, is conclusive, and only a strong subjective bias in favor of another hypothesis can distort or ignore this evidence. The applicability of laboratory work to the field should be demonstrable in the field as well as in the test tube.

STEPHEN ROYCE.

CRYSTAL FALLS, MICH.

REVIEWS

Petrography and Petrology, by FRANK F. GROUT. Pp. 552, figs. 266. McGraw-Hill Book Co., New York, 1932. Price, $5.00.

Although the use of superlatives in reviews of scientific books is generally not desirable, it seems impossible to refer to this book in anything less than the most enthusiastic terms.

The plan of the book is simple, the threefold subdivision of rocks being observed, and sections on the petrography of each group are followed by discussions of the petrology.

Petrography is a difficult subject to discuss. On the one hand is the danger of becoming bogged in a mass of detail, much of which is irrelevant or unimportant, and on the other hand there are the pitfalls of classification which, if once entered, generally lead the author to devise a new system which he can use successfully, but which is not available to the majority of petrographers unless they are willing to indulge in an enormous amount of calculation in order to reduce all rocks to this system or else use a combination which is probably not satisfactory either to themselves or other petrographers.

Grout uses a simple system, based on the mineralogical classification, in which he groups rocks into clans and then subdivides them into species based upon (*A*) textural and structural features and (*B*) important mineralogical varieties. The majority of the special locality terms with which petrographers have so long suffered are placed in a subordinate position.

The petrographic sections are divided as follows: Igneous rocks (pp. 29–142) sedimentary rocks (260–304) metamorphic rocks (350–374) and mineral tables (443–478).

In the case of the igneous rocks it seems as if the textural, mineralogic, and special varieties which Grout discusses might have been grouped together, with brief statements in the discussion of each clan describing variations from the general rule and peculiarities of that clan. As it is, many of these general features are taken up under the rhyolite-granite clan; a plan which seems to overemphasize the importance of variations in this clan. Thus, "Notes on the rhyolite-granite clan" occupy approximately seven pages, and "Minerals of the granite clan" another seven pages, but these topics are discussed in four pages in the case of the andesite-diorite clan.

It also appears as if too little emphasis was placed upon the correlation of beds by means of residues—either heavy mineral or insoluble.

In the petrologic sections—igneous rocks (143–259), sedimentary rocks (305–349) and metamorphic rocks (375–442) the book achieves greatness. Grout conceives "petrology" to include mode of formation, relation to earth processes, and a discussion of all related physical and chemical data. With the enormous accumulation of publications on the theoretical side of petrology available, the author who can succeed in separating speculation from theory and weld the whole mass into a readable volume can consider that he has literally performed wonders. In almost every paragraph Grout weighs evidence, presents speculations and theories as such and in addition presents clearly the residuum of fact which is inherent in almost every hypothesis.

Nowhere in the book is one led to think that the author is leading to a pet hypothesis of his own, in fact he might actually be criticized for stressing his own views and those of his associates as little as he does.

The reviewer notes a lack of reference to current continental European books, not only throughout the text but also in the valuable lists of selected readings. To cite but two examples, the classifications of Niggli and von Wolff do not seem to be referred to, nor do Stille, Kober, and Haarmann appear to be mentioned, although there is considerable reference to theories of earth shrinkage, isostasy and continental drift (Wegener's but not Taylor's).

In attempting to classify this book according to the class of geologists for whom it may be most useful, the reviewer feels that none who deals with rocks can afford to be without it. For the student, the very practical descriptions and the tables make the book an excellent text, which, of course, must be supplemented by lectures. For the teacher and the graduate student, the book appears to be of great value not only for the way in which the subject is treated, but for the excellent and concise way in which it deals with present-day theories. Finally, the practising geologist will find in its concise tables of criteria and its discussion of practically every phase of rock science a hand book which cannot fail to stimulate him and to direct his observations along lines which will prove most fruitful.

The publishers have produced an excellent book with practically no typographical errors. The author is to be congratulated upon the result of his years of study and preparation and the geological fraternity is to be congratulated upon having available one of the great contributions to geological literature.

W. V. Howard.

University of Illinois,
Urbana, Ill.

The Geology of Malaya. By J. B. SCRIVENOR. Pp. 217, figs. 33, geol. map. Macmillan Company, London, 1931. Price, $6.50.

This handy volume, written by one who knows his subject well, is a companion to a preceding volume by the same author on "The Geology of Malayan Ore Deposits." It deals with the perplexing geology of this region, with particular attention to the rock formations and their structure. A chapter of more than usual interest is that on Weathering and Laterite, and the chapter on Metamorphism deals with the interesting tourmaline-corundum rocks. Another chapter deals with mineralogical notes and tektites. Ores are not considered in this volume, but an extensive bibliography covers the ore deposits.

ALAN BATEMAN.

An Introduction to Geology. 3rd. Ed. By W. B. SCOTT. Vol. I, Physical Geology, pp. 604, figs. 264. Price, $3.50. Vol. II, Historical Geology, pp. 485, figs. 265–389. Price, $3.00. The Macmillan Company, New York, 1932.

The long wished-for new edition of the well-known text-book by Dr. Scott has at last appeared. It is rewritten throughout, since "the last twenty-five years have produced an immense quantity of geological literature and in endeavoring to incorporate the requisite amount of the new material in this book it was necessary to rewrite it altogether and to adopt a new order of treatment." It is unnecessary to call detailed attention to the differences in the order of treatment of topics in the old and the new edition, for as the author states in his preface, "it is perfectly feasible to make use of the book in such different order of chapters as the instructor may prefer." In the new edition there is a large expansion in the chapters on the igneous rocks and vulcanism, and there are large extensions to the sections on the geology of the continents other than North America. Moreover, there have been incorporated in the text at various places more definite statements as to the origin and migration of mammals, and as to plant evolution. New features are the section on Ancient Man, and the adoption of the idea of evolution "as the only possible explanation of geological history." In the earlier editions the idea of evolution was not employed for this purpose.

For many teachers the book is improved by the addition of short lists of references at the ends of the chapters and by very comprehensive indexes.

It is naturally impossible in a brief review to outline all of the many features of the new edition, or to criticize the statements referring to debatable subjects. It is enough to state that the general style of the book

is the same as that of earlier editions, and that the statements in reference to debatable subjects are largely matters of personal opinion.

The book is different enough from other text-books of geology to be preferred by many teachers of beginning classes. It covers the field in a satisfactory way, is not too detailed, and is well printed. Some of the half-tones, however, are not as clear as they should be.

W. S. BAYLEY.

A Text Book of Mineralogy. By E. S. DANA. 4th edition, by W. E. FORD. Pp. 851, figs. 1089. Wiley & Sons, New York, 1932. Price, $5.50.

This edition follows just ten years later than its widely known predecessor, and has undergone a more drastic revision than any of the earlier editions. The size has been increased by 130 pages; descriptions of 220 new species have been included; mention is made of doubtful species or those that have recently been discredited. The book now contains a brief description of *all known* minerals. In this respect it is invaluable, for it is the only book that does.

In Part I., Crystallography, 17 new pages have been added on x-ray investigations of crystal structure. Part IV., on the Origin, Mode of Occurrence, and Association of Minerals, is entirely new. Part V., Descriptive Mineralogy, is completely revised. Under the description of each mineral are now included—where available—results of investigations of mineral structure by x-rays; occurrences have been largely rewritten, and all known localities are given for the rare minerals.

With the changes mentioned above, and the retention of all the valuable features that made its predecessor the leader of text books on mineralogy, this book now stands supreme. It is a worthy descendant from a well known lineage. Professor Ford is to be congratulated for his perspicacious thoroughness and assiduous labors, and the publisher for the production of an excellent example of bookmaking. Every one interested in mineralogy should own a copy.[1]

ALAN BATEMAN.

An Introduction to the Mathematics of Map Projections. By R. K. MELLUISH. Pp. 145. Cambridge University Press, Cambridge, England, and The Macmillan Co., New York, 1931. Price, $3.00.

This book deals comprehensively with the theories underlying the construction of maps. It is intended for the student of mathematical geography who has a fair knowledge of calculus. It deals with the properties of the four main classes of projections and the method of comparing them with one another, the question of finite measurements, and a discussion of the best projection for a given area.

[1] Those who desire a copy may obtain it through our Journal Bookshop, by writing to Professor W. S. Bayley, Urbana, Ill.

The Universe Unfolding. By R. H. BAKER. Pp. 140, figs. 7, pls. 7. Century of Progress Series, Williams and Wilkins, Baltimore, 1932. Price, $1.00.

The Century of Progress Series undertakes, in a set of volumes by well known scholars, to present the essential features of the fundamental sciences. This handy little volume gives an account of the Universe in simple language. First, the reader is told what the ancients thought about it, and is led through the development of astronomical science to its present state. The various kinds of stars and star groups are discussed, also the Milky Way and what lies beyond. The book is interestingly written and can be enjoyed by everyone.

Stratigraphy of Plains of Southern Alberta. Donaldson Bryant Dowling Memorial Symposium. Pp. 166, illus. 60. Cloth, 9 x 6. Amer. Assoc. Petrol. Geol. Tulsa, Okla., 1931. Price, $3.00.

Fourteen papers by members of the Alberta Society of Petroleum Geologists and the American Association of Petroleum Geologists are here collected in a handy little volume, which contains practically all that is known of the stratigraphy of the district discussed. The papers were originally published in a slightly different form in the *Bulletin* of the American Association. After the discussions that their original presentation developed, the papers were revised in many points so that they now "may be regarded as the work of the Alberta Society as a whole." The volume opens with a short suggested correlation of the formations in Alberta with those in Montana, and an attempt to simplify the correlation throughout the entire geosyncline extending from Alberta as far south as New Mexico. The author, J. S. Irwin, does not expect his scheme of correlation to be accepted at once, but offers it as a basis for the consideration of workers in the general area. The following papers describe in some detail the different formations met with in Alberta and discuss their relations to associated ones.

The book is well illustrated with maps, sections, and half tones.

W. S. BAYLEY.

BOOKS RECEIVED.

BY

DAVID GALLAGHER.

Canada Geol. Survey, Summary Report, 1931, Part B. Pp. 84, figs. 8. Ottawa, 1932. Contains: The Mesozoic-Paleozoic Contact and Associated Sediments, Crowsnest District, Alberta and B. C., by B. R. MACKAY; Stratigraphy and Structure of the Eastern Portion of the Blood Indian Reserve, Alberta, by L. S. RUSSELL; Oil Prospects of the Fisher

Creek, Two Pine, and Birch Ridge Structures, Eastern Foothills of Alberta, by G. S. HUME; The Darmody-Riverhurst Artesian Water Area, Southern Saskatchewan, by D. C. MADDOX; Deep Borings in the Prairie Provinces, by W. A. JOHNSTON.

Geologic Reconnaissance of the Dennison Fork District, Alaska. By J. B. MERTIE, JR. Pp. 43, pls. 8, figs. 3. U. S. Geol. Surv. Bull. 827. Washington, 1931. Price, 45 cts. Contains topographic and geologic maps, scale 1:250,000.

La Géologie et les Mines de L'Indochine Française. By F. BLONDEL. Pp. 148, map. Annales de l'Académie des Sciences Coloniales, Tome V. Paris, 1932.

Géologie de la Mediterranée Occidentale. Vol. I, Part II, Nos. 3–5, April, 1930. Pp. 145, photographs. Descriptions of excursions in Catalonia, XIV International Geological Congress, 1926. **Vol. II, Part I,** Nos. 1–4, October, 1930. Pp. 64. Four papers on parts of Catalonia by Congressionalists.

Annual Report of the Director, Serv. Geol. e Min. do Brazil, 1930. Pp. 76. Rio de Janeiro, 1931.

Chrome, Molybdenum, Nickel, and Tungsten in Brazil. Pp. 52. Serv. Geol. e Min. do Brazil, Bull. 56. Rio de Janeiro, 1931.

Graphite. By E. P. SCORZA. Pp. 32. Serv. Geol. e Min. do Brazil, Bull. 57. Rio de Janeiro, 1931.

Geology of Southwestern Uganda. By H. A. STHEEMAN. Pp. 144, photos 94, figs. 102, sections 6, maps 6. Martinus Nijhoff, The Hague, 1932. A most excellent treatise with especially interesting part on tin deposits.

Geology and Mineral Resources of the Roanoke Area, Virginia. By H. P. WOODWARD. Pp. xv + 172, pls. 29, figs. 8. Va. Geol. Surv. Bull. 34. University, Va., 1932. Physiography, stratigraphy, structural, historical, and economic geology of the area.

Geology and Mineral Deposits of a Part of Southeastern Manitoba. By J. F. WRIGHT. Pp. 150, figs. 9, map. Canada Geol. Surv. Mem. 169. Ottawa, 1932. Price, 25 cts.

Geology of Randolph County (W. Virginia). By D. B. REGER. Pp. 989, pls. 74, figs. 30, 2 colored maps in separate atlas. W. Va. Geol. Surv. County Reports. Morgantown, 1931. History and physiography, geology, mineral resources, paleontology.

Surface Water Supply of Hawaii. By N. C. GROVER. Pp. 101. U. S. Geol. Surv. Water-Supply Paper 675. Washington, 1932. Price, 20 cts. Gaging-station records.

Surface Water Supply of Southeastern Alaska, 1909–1930. By F. F. HENSHAW. Pp. 81, pls. 3, 1 fig. U. S. Geol. Surv. Bull. 836-C. Washington, 1932. Price, 10 cts.

New Zealand Geol. Surv. Annual Report, 1930–31. By J. HENDERSON. Pp. 12. Wellington, 1931. Report of the year's work.

Iron Ores, Present and Future. By W. O. HICKOK. Pp. 6. Penn. Topog. and Geol. Surv. Bull. 104, 1932.

Shinyanga Diamond Fields. By E. O. TEALE. Pp. 39, map. Tanganyika Geol. Surv., Short Paper No. 9. Dar es Salaam, 1931. Price, 4/.

Tanganyika Geol. Survey, Annual Report, 1930. By E. O. TEALE. Pp. 34. Dar es Salaam, 1931. Price, Shs. 2/50. Account of year's work, and brief geological descriptions.

Geology and Coal Resources of the Raniganj Coalfield. By E. R. GEE. Pp. 343, pls. 20, figs. 2. India Geol. Surv. Mem. LXI. Calcutta, 1932. Price, Rs. 13–6 or 22/. A comprehensive and detailed monograph with fine maps.

Mineral Industry of New Jersey for 1930 and Preliminary Estimate for 1931. By M. E. JOHNSON. Pp. 25, pls. 5. Dept. of Conserv. and Devel. of New Jersey, Geol. Ser. 37, 1932.

China-Clay (Kaolin). Pp. 100. Imperial Institute, London, 1931. Price, 1/6. Summary of world occurrence, production, and uses, with excellent bibliography.

The Jackson Gas Field, Hinds and Rankin Counties, Mississippi. By W. H. MONROE. Pp. 17, pls. 2. U. S. Geol. Surv. Bull. 831-A. Washington, 1931. Price, 10 cts. Geology, development, production.

Progress Report on the Study of Southern Illinois Silica as a Pottery Material. By C. W. PARMELEE. Pp. 5. Illinois Geol. Survey, Rpt. of Inves. 24. Urbana, 1932.

List of Publications, U. S. Bureau of Mines, 1910–1931, with an Index by Subjects and Authors. Pp. 241. U. S. Dept. Com., Bureau of Mines. Washington, 1932.

Copper Deposits Near Keating, Oregon. By J. GILLULY. Pp. 32, pls. 3, figs. 2. U. S. Geol. Surv. Bull. 830-A. Washington, 1931. Price, 15 cts. Geology, mineral deposits, economic considerations.

Bibliography of Seismology, No. 12, Oct., Nov., Dec., 1931. By E. A. HODGSON. Pp. 18. Dominion Observatory, Ottawa, Pub. vol. X. Ottawa, 1932. Price, 25 cts.

General Outlook on the Situation of the Iron, Chromium, Manganese and Pyrite Deposits of Roumania. By T. P. GHITULESCU AND I. GAVĂŢ. Pp. 30, map. Roumanian Geol. Survey. Bucharest, 1931.

Highway Geology of Oklahoma. Pp. 68. Contribution of the Okla. City Geol. Soc. to the 17th Ann. Convention of the Am. Assoc. Petr. Geol. Oklahoma City, 1932. Geology by the mile.

SCIENTIFIC NOTES AND NEWS

Walter C. Mendenhall, Director of the U. S. Geological Survey, was given the degree of Doctor of Science at the University of Wisconsin on June 20.

Sir Alfred Kitson, formerly Director of the Gold Coast Colony Geographical Survey, has gone to Kenya to inaugurate a geological survey there.

Richard Stappenbeck, of the University of Berlin, left Germany in June to take up work in the Argentine oil fields for the Dirección General de Yacimientos Petroliferos Fiscales, Paseo Colon 922, Buenos Aires.

Anton Gray has gone from England to Serbia, where he will carry on geological work for Trepca Mines and other Selection Trust properties.

C. H. E. Stewart, of Toronto, Canada, has gone to Great Bear Lake to supervise development and exploration.

W. H. Collins, Director of the Canada Geological Survey, has been elected a member of the American Philosophical Society.

C. K. Leith has been nominated for the presidency of the Geological Society of America for 1933. He conducted a round table discussion on minerals at Portland, Oregon, July 11 to 15, under the auspices of the Institute of International Relations.

E. L. Bruce, of Kingston, Ontario, was recently elected president of Section IV (Geology) of the Royal Society of Canada.

Arthur W. Rogers has retired from the post of Director of the Geological Survey, Union of South Africa, after 36 years of Government service in the Cape and Transvaal.

E. T. Mellor has gone to England from Johannesburg.

Chester W. Washburne has received the honorary degree of Doctor of Science from the University of Oregon. He has recently been giving lectures on Normal Faulting at Princeton, Cincinnati, Stanford, and Louisiana, Texas, California and Oregon State universities.

J. F. Wright, of the Geological Survey of Canada, has been elected a Fellow of the Royal Society of Canada.

A. L. Hall, of Pretoria, South Africa, is now regional vice-president of the Society of Economic Geologists for Africa.

Paul Fourmarier, professor of geology at Liege, Belgium, has been visiting the iron and copper mines of Michigan and Minnesota.

David White, of the U. S. Geological Survey, has received from the National Academy of Sciences the Mary Clark Thompson gold medal for his distinguished work in paleontology.

A. J. McNab has returned to London from Northern Rhodesia.

Charles A. Mitke, who is now in the Southwest, has been examining the Vekol Mine, south of Casa Grande, Arizona.

George J. Young has lately severed his connection with the Engineering and Mining Journal as Western editor.

W. E. V. Abraham, geologist for the Burmah Oil Company, Ltd., has been spending several months in the United States investigating geological and production problems.

Warren S. Smith is returning to this country after two years of geological and exploration work at the Magnitogorsk iron deposits in Russia.

The fifth meeting of the Deutsche Geologische Gesellschaft devoted exclusively to economic geology was held at Hanover recently, and the oil geology of the North German and of the new and promising Thuringian oil fields was discussed. The discussions for the four preceding years have been: the North German potash deposits, Bituminous coal, Brown coal, and Iron ores; for the coming year, Groundwaters and mineral springs.

The following large copper mines have closed down for at least part of the summer, some of them probably for a longer time: Utah Copper, Nevada Consolidated, Ajo, Magma, Inspiration, Miami, Verde, Mohawk, and most of Morenci.

The U. S. Geological Survey, after twenty years of search and examination of prospects, has concluded that the idea of producing commercial nitrate from deposits within the United States should be given up and the country must resign itself to dependence upon by-product or synthetic sources of nitrogen or upon imported nitrate.

The Field Conference of Pennsylvania Geologists had its second annual meeting May 28–29 in the Lehigh Valley as guests of Lafayette College and Lehigh University. About 75 persons attended. B. L. Miller headed economic excursions for non-metallics to the slate and cement belts, inspecting mills and quarries. Other trips included the metallic paint mine near Palmerton and the abandoned iron and zinc mines south of Bethlehem. Non-economic trips covered the Paleozoic and Triassic, and some interesting glacial deposits of the Delaware Valley.

J. W. Gregory, professor of geology, Glasgow University, and president of the Geological Society of Great Britain, was drowned on June 2, on the Upper Amazon, by the capsizing of a canoe while he was en route for the Andes to study volcanic action.

Copies of books mentioned under "Reviews" or under our "New Book List" (see advertisement page) may be purchased through our Journal Bookshop by writing to W. S. Bayley, University of Illinois, Urbana, Ill.